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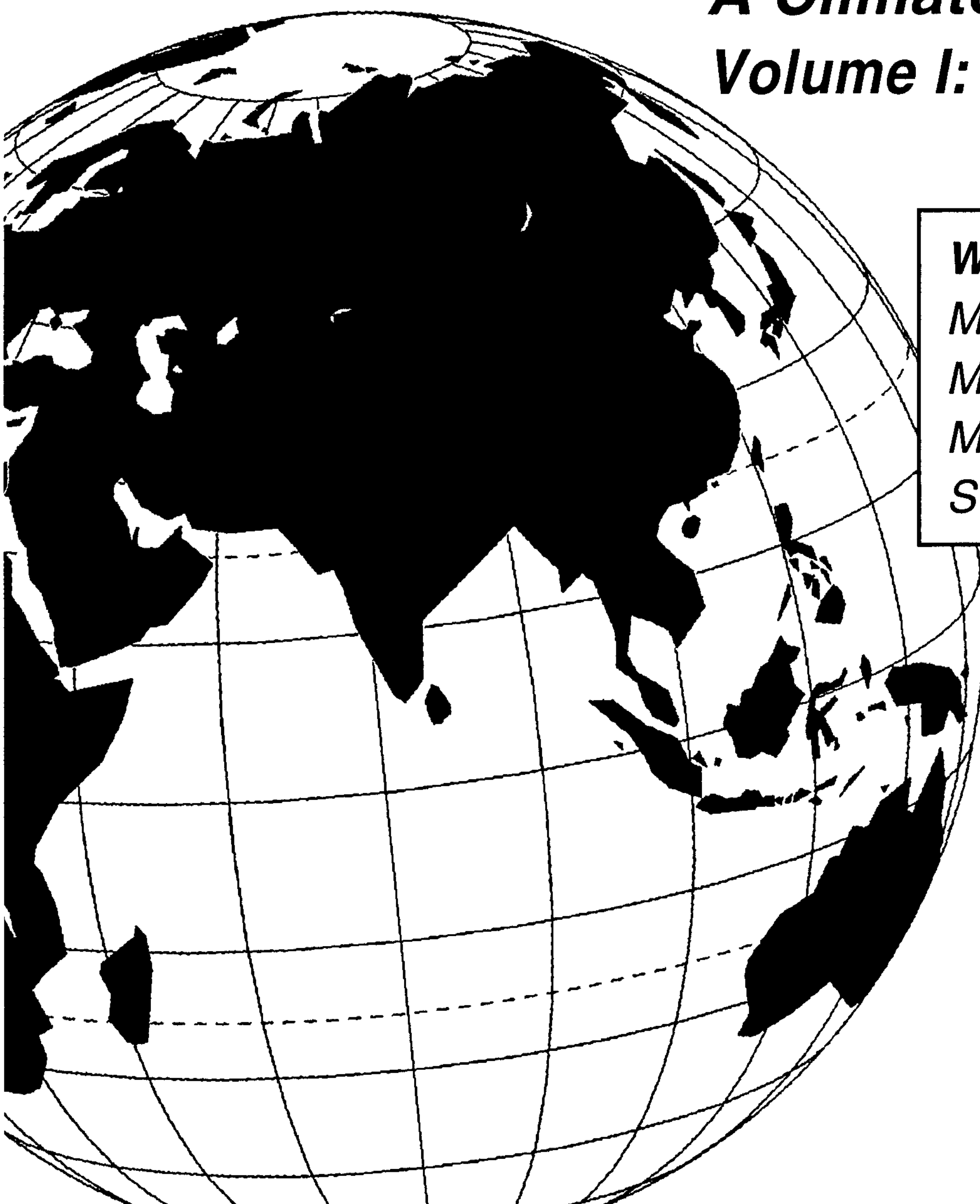
South Asia

A Climatological Study
Volume I: Subtropical South Asia

Written By:
Mrs. Melody Higdon
Mr. Robert Lilianstrom
Mr. Virgil H. Killman
SSgt Gary Clinton



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Air Force Combat Climatology Center
151 Patton Avenue, Room 120
Asheville, North Carolina 28801-5002

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Program Manager

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13. Abstract: This technical note is a climatological study of Subtopical South Asia. After describing the geography and major meteorological features of the entire region, the study discusses in detail the climatic controls of each of Subtropical South Asia's "five zones of climatic commonality." Each "season" is defined and discussed in considerable detail with emphasis on general weather, hazards, clouds, visibility, winds, precipitation, and temperature.

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PREFACE

This study was prepared by the Air Force Combat Climatology Center's Climate Analysis Team (now AFCCC/DOC5) in response to a support assistance request (SAR) from the Air Force Weather Agency, Offutt AFB, Nebraska.

Thanks to all the people in AFCCC's Operational Climatology Branch, who provided the immense amount of data required for the preparation of this regional climatology study. The work of Master Sergeant Joan Bergmann was especially appreciated.

Finally, the authors owe sincere gratitude to the technical editors and graphics illustrators, past and present—Mr. Gene Newman, Mr. Mike Jimenez, Technical Sergeant Gina Vorce, and Staff Sergeant Kurt Riley. Without their patience, cooperation and creativity, this project would not have been possible.

Major Joe King
Chief, Climate Analysis Team

Chapter 1

INTRODUCTION

Area of Interest. This study describes the topography, climatology, and meteorology of South Asia. The regional has been subdivided into ten zones of climatological commonality.

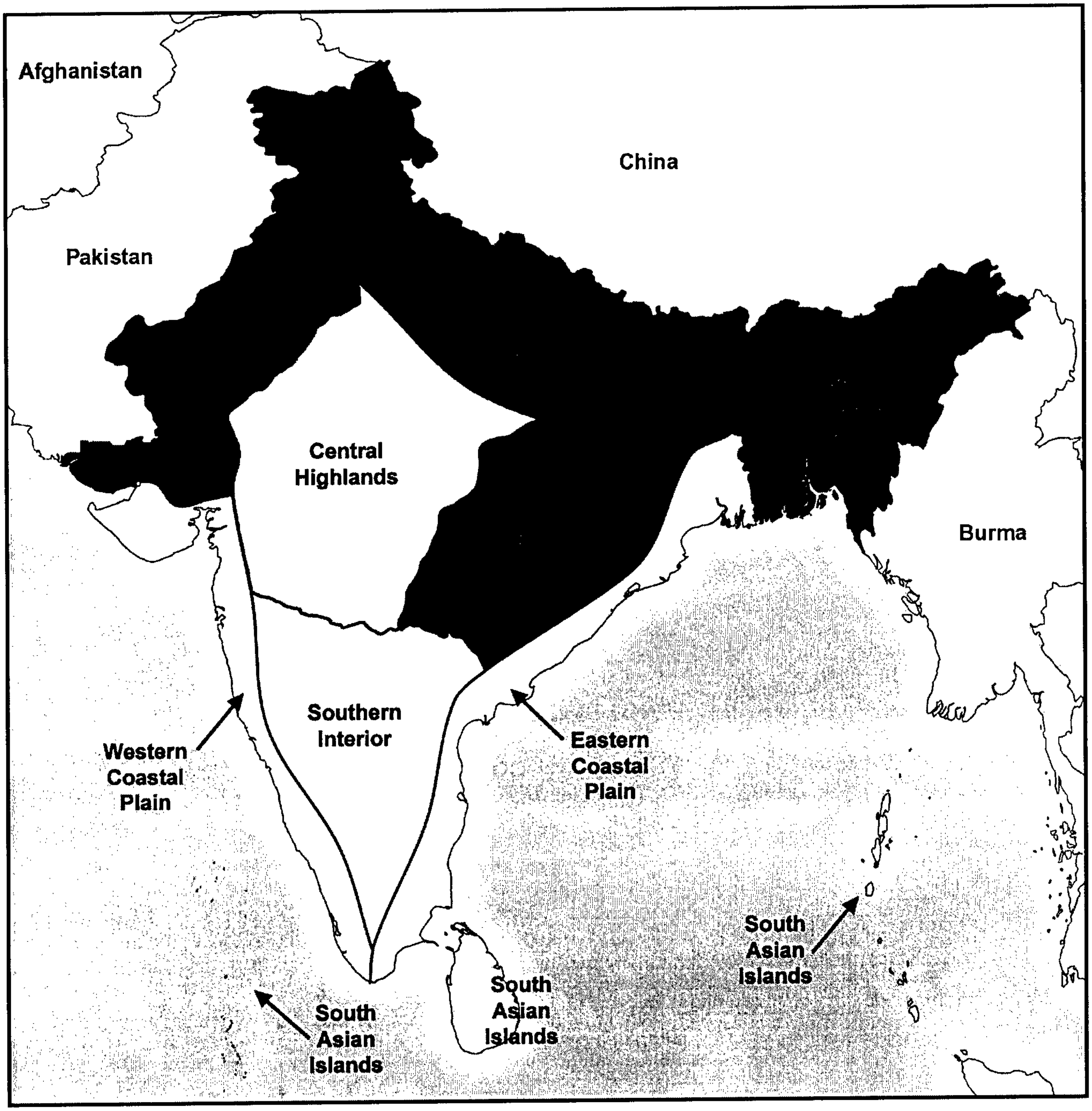


Figure 1-1. Subtropical South Asia.

Introduction

South Asia. For the purpose of this study, South Asia has been divided into two volumes, which are further subdivided into 5 zones each. This volume, Volume I, covers the following zones:

Eastern Coastal Plains. This area includes the eastern coast of India from Cape Comorin, at the tip of the peninsula, to the Bangladesh border. It goes from the coast to the foot of the Eastern Ghats. The boundary of this area follows the Bangladesh border to roughly 24° N and tracks inland to the Chota Nagpur Plateau and the eastern flanks of the Eastern Ghats. East of the Chota Nagpur Plateau, the Ganges basin, which includes most of Bangladesh, begins at the foot of the plateau and extends east to the mountains of northeastern India.

Southern Interior. This region, sandwiched between the two peninsular mountain ranges, includes the Deccan (also known as the Deccan Plateau) from the Godavari River (roughly 19° N) southward to the end of the Cardamom Hills, which are the juncture of the Western and Eastern Ghats at the tip of the peninsula. The Eastern Ghats to the Godavari River and the eastern slopes of the Western Ghats (to the ridge line) are included in the region.

The Western Coastal Plains. The western coastal plains are a long, narrow strip of land between the Arabian Sea and the Western Ghats. The area begins at 22° N, 69° E on the south coast of the Gulf of Kutch. The north boundary extends 250 miles (400 km) east northeast. Near Ahmadabad, the boundary extends south for 1,025 miles (1,650 km) to Cape Comorin at the tip of the peninsula.

Central Highlands. The region is bounded by the Indo-Gangetic plain to the north, the Aravalli Range to the northwest, the Western Ghats to the west, and the Godavari River to the south. The eastern boundary is along the Son River on the western rim of the Chota Nagpur plateau, then along the Narmada River westward to 80°E, then southward with the Wainganga and Pranhita Rivers along 80° E to the Godavari River.

Ocean Islands. This region includes Sri Lanka, the Andaman Islands, the Nicobar Islands, the Lakshadweep Islands, and the Maldives. Sri Lanka is just off the southeastern tip of the India peninsula. The Andaman Islands and the Nicobar Islands are in the southeastern corner of the Bay of Bengal. The Lakshadweeps and the Maldives are off the southwest tip of the Indian peninsula in the Arabian Sea and Indian Ocean.

Study Content. Chapter 2 provides a general discussion of the major meteorological features that affect South Asia. These features include climatic controls, synoptic disturbances, and mesoscale and local features. The individual treatments of each region in subsequent chapters discuss how these features uniquely affect that particular region. Meteorologists using this study should read and consider the general discussion in Chapter 2 prior to trying to understand or apply the individual climatic zone discussions in Chapters 3 through 8. This is particularly important because this study was designed with two purposes in mind: first, as a master reference for South Asia; and second, as a modular reference for each region. Chapters 3 through 8 amplify the general discussions in Chapter 2 by discussing the topography, climate, and meteorology of the zones of climatic commonality shown in Figure 1-1. These chapters provide detailed discussions in the reasonably homogenous zones of climate and meteorology. In mountainous areas, however, weather and climate are not necessarily internally homogenous. Conditions can be distinctly different in two locations which are geographically close yet topographically far apart.

In each region, topography is discussed first (including terrain, rivers and drainage systems, lakes, water bodies, and vegetation). Next, major climate controls, and, if appropriate, special climatic features are described. Weather for each season is then discussed, organized in the following order:

- General Weather
- Sky Cover
- Visibility
- Winds
- Upper-Air Winds
- Precipitation
- Temperature
- Hazards

Conventions. The spelling of place names and geographical features are those used by the National Imagery and Mapping Agency (NIMA). Surface distances and elevations are in feet with conversions to meters or statute miles (miles) with conversions to

kilometers (km). Wind speeds are in knots. Cloud and ceiling heights are reported in feet. When the term "ceiling" is used, it means 5/8 cloud coverage at and below any level unless otherwise stated. Cloud bases are above ground level (AGL) and tops above mean sea level (MSL) unless specified otherwise. Temperatures are in degrees Fahrenheit (°F) with conversions in degrees Celsius (°C). Wind speeds are in knots. Precipitation amounts are in millimeters (mm) up to 1,000 mm. From that point higher, amounts are in meters. Pressures are given in millibars (Mb). Latitude and longitude are listed in degrees north, south, east or west (example: 55° N). Charts are labeled in Universal Coordinated Time (UTC or "Z" (Zulu) time) or in local time (L). Visibility is in statute miles (miles) with conversions to kilometers (km) except for times when visibility is 9,000 meters or below. Then conversions will be to meters. Thunderstorm days are those on which they have been reported. Precipitation days include those with any type of precipitation.

Data Sources. Most of the information used in preparing this study came from two sources, both within AFCCC. Studies, books, atlases, and so forth were supplied by the Air Force Weather Technical Library (AFWTL or AFCCC/DOR). Climatological data came directly from the Air Weather Service Climatic Database through AFCCC/DOB- the branch responsible for maintaining and managing this database.

Related References. This study is certainly not the only source of climatological information for the military meteorologist concerned with South Asia. Staff weather officers and forecasters are encouraged to contact the Air Force Weather Technical Library (AFWTL) in Asheville, North Carolina for more information.

Chapter 2

MAJOR METEOROLOGICAL FEATURES

List of Topics

Sea-Surface Conditions. Ocean currents play an important role in the region's climate. The major currents are shown in Figure 2-1 and described below. The strength and position of most of these currents fluctuate during the year, but the South Equatorial Current exists year-round.

The Indian Ocean's South Equatorial Current is strongest in August, when it forms a large, clockwise eddy with the Southwest Monsoon Current. The Southwest Monsoon Current, present from June through October, brings warm water into the northern Arabian Sea. The North Equatorial Current replaces it in December. The North Equatorial Current is strongest in January and February when a large clockwise eddy forms in the Bay of Bengal. To the south, a weak eddy flow separates it from the Equatorial Counter Current. The eastward-flowing Equatorial Counter Current is active between December and April. Its southern boundary is ill-defined as it merges into the South Equatorial Current, but the northern boundary is sharp. Figure 2-2 shows mean sea-surface temperatures (SSTs). They are above 77°F (25°C) all year except in the northern Arabian Sea and in the northern Bay of Bengal where several large rivers feed colder water into these areas during winter.

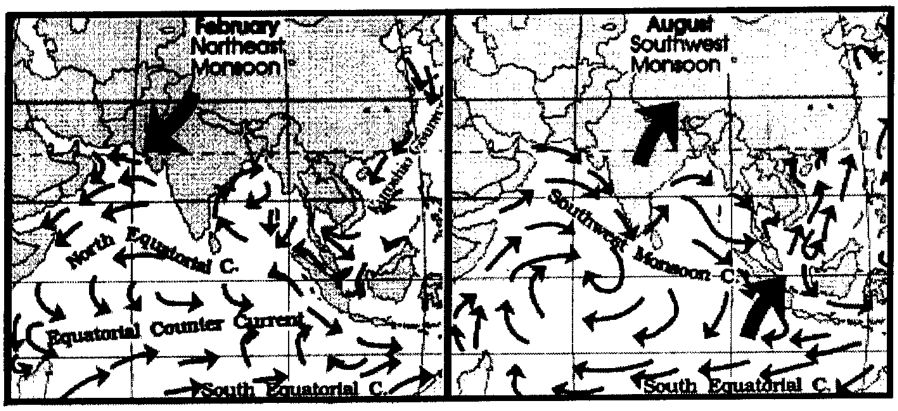


Figure 2-1. Ocean Currents during February and August. Large arrows indicate prevailing wind direction. (Traxler, et al, 1997 from Wells, 1986)

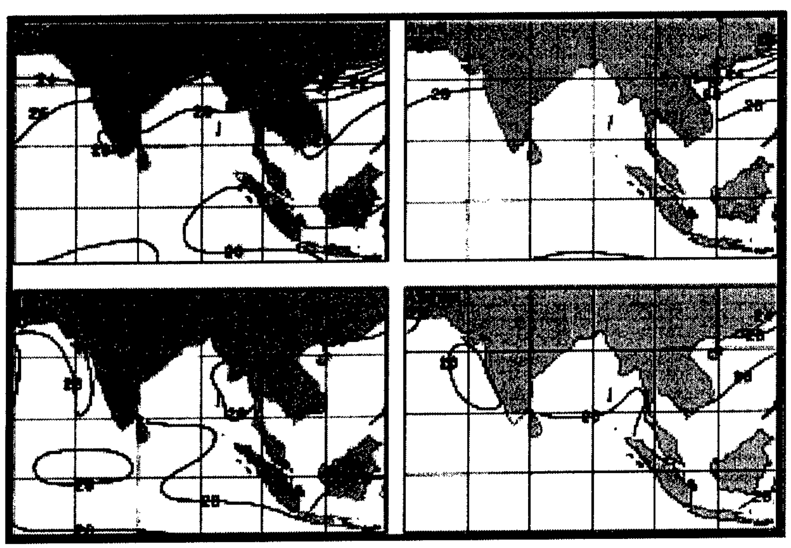


Figure 2-2. Mean Sea-Surface Temperatures. The figure shows the temperatures in degrees Celsius (°C). (Adapted from NAVAIR 50-1C-65, Vol. IX, 1965)

Semipermanent Climate Controls

Major Pressure Features. These features include: the South Indian Ocean (Mascarene) high, Asiatic high, North Pacific high, Australian high, Australian low, Indian high, the Asiatic low, and the India-Myanmar trough.

South Indian Ocean (Mascarene) High. This semipermanent, Southern Hemisphere high-pressure cell provides cross-equatorial flow in April through October (see Figure 2-3). Mean core pressure ranges from 1021 mb in April to 1028 mb in August though it can exceed 1040 mb during Southern Hemisphere winter. Annual movement is mainly east-west from 30° S, 87° E in January to 29° S, 65° E in July. The high slopes equatorward and westward with height. The cross-equatorial flow from this high is a primary driver of the southwest monsoon. Its east-west shifts cause seasonal variations in the strength of the equatorial westerlies.

Asiatic High. This strong, shallow high-pressure cell, also called the Siberian high, is in place over Asia from late September to late April. It rarely extends above 850 mb. The mean central pressure is strongest (1038 mb) in January, when the high is centered over western Mongolia. The Asiatic high is created and supported by radiational cooling, though migratory arctic air masses intensify it and produce multiple centers. The core pressure may exceed 1050 mb for up to 3 days--the highest recorded pressure is 1083 mb. The Himalayas block most cold air from this high, but modified air reaches the region from the east.

North Pacific High. This subtropical high, centered off the North American coast, is farthest north and west in July. In January, it forms a ridge near 25° N. In July, the ridge is near 35° N and extends west into the South China Sea. Its position is linked to the movement of the equatorial trough (ET).

Australian High. This thermal high exists in Southern Hemisphere winter. It is strongest in July, when it is near 28° S, 128° E, with a mean central pressure of 1022 mb. It is not as strong or persistent as the Asiatic high and is regularly traversed by disturbances and

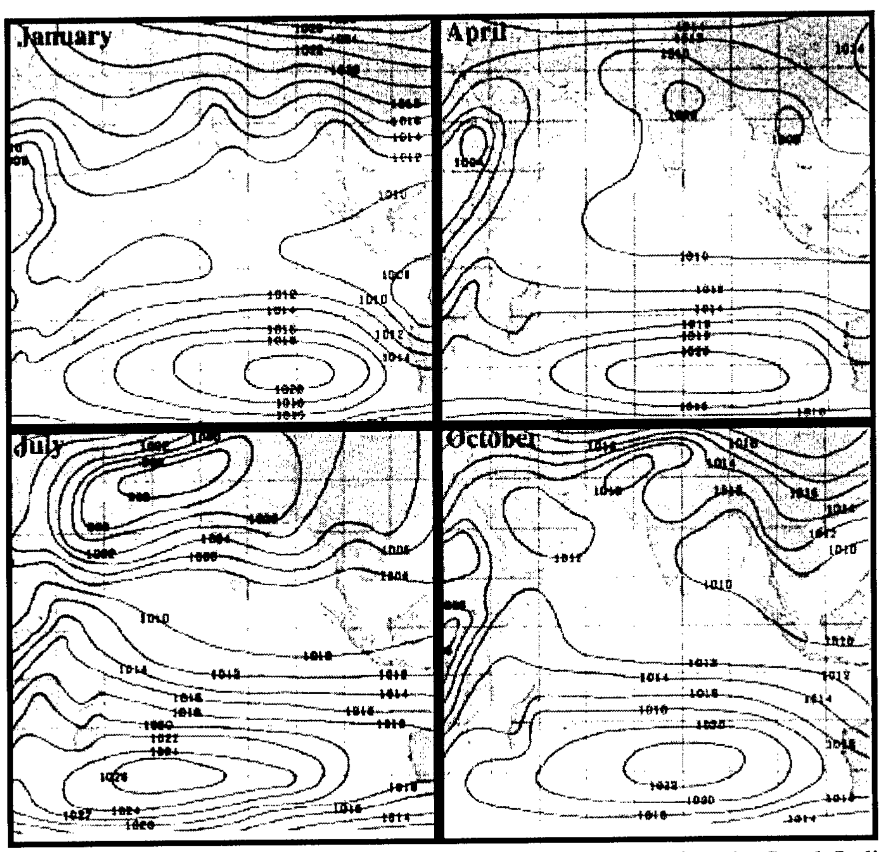


Figure 2-3. Mean Sea-Level Pressure. The figure clearly depicts the South Indian Ocean high-pressure system. (Traxler, et al, 1997 adapted from Gadgil, 1977)

migratory highs. It is a component of the Indian Ocean monsoon system.

Australian Low. This is a thermal low that develops over Australia during the Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

Indian High. This thermal high sets up on an irregular basis during the northeast monsoon. Because its intensity and position are highly variable, it is not evident in the mean charts shown in Figure 2-3. This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area. Its impact on the weather regime varies with strength and position. Although always weak, when the high is strongest, it tends to push the leeside trough into the mountains and block low-pressure systems from tracking across the south foot of the Himalayas. The farther north it develops, the more likely this will happen. When the high is weakest, it tends to intensify the leeside trough without shifting it. Western disturbances reintensify in this trough.

Asiatic Low. From May to early October, this low, also called the Thar or Pakistani heat low, anchors the eastern end of a broad, low-level thermal trough that extends from northwestern India across southern Pakistan, Iran, Saudi Arabia, and into the Sahara. The low, normally cloud-free, is strongest in July when its central pressure averages 994 mb. Its mean position in July is near 35° N 65° E (see Figure 2-3). This thermal low also draws in the ET and anchors its western end. Flow around the Himalayas dynamically enhances the troughing in India. This thermal low replaces the Asiatic high during the Northern Hemisphere summer and is, in turn, replaced by it in winter.

India-Myanmar Trough. This quasi-stationary trough develops in the summer along 85° E south of the Himalayas. Figure 2-4 shows the trough's mean position during the southwest monsoon. The tropical easterly jet (TEJ) over the Bay of Bengal intensifies convection along the trough, which is a preferred area for the development of monsoon depressions.

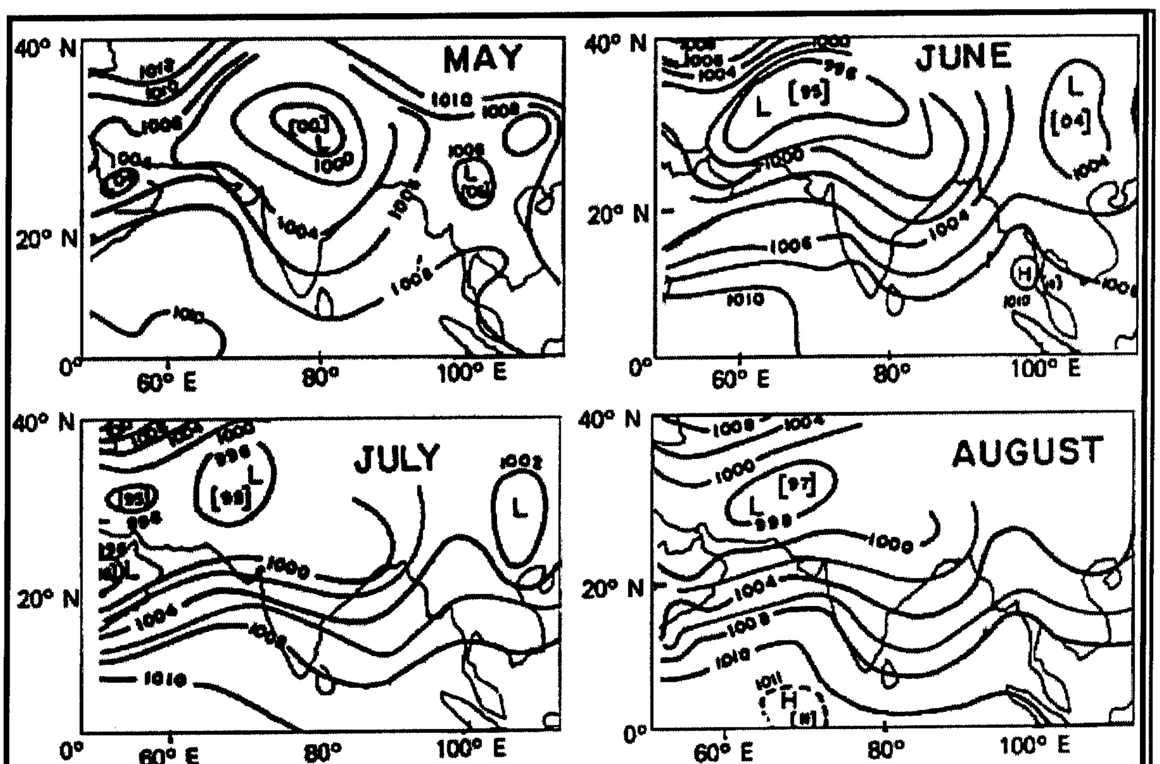


Figure 2-4. Mean Monthly Sea-Level Pressure Charts for May through August. This figure depicts development of the Indian-Myanmar Trough. (Adapted from Gadgil, 1977)

Semipermanent Climate Controls

Ocean Surface Wind Flow Pattern. January's wind field shows the northeast monsoon in full swing. Northeasterly winds from the Asiatic high sweep across the northern Indian Ocean (see Figure 2-5). The flow becomes northwesterly near the equator and meets the Southern Hemisphere's trades, which become southwesterly near the equator at the equatorial trough (ET). By April, the transition to the southwest monsoon begins as the northerly flow weakens. Meanwhile, the ET begins to shift northward, but remains south of the equator. The south Indian Ocean high strengthens and shifts west by the end of April to set up the strong, south-to-north, cross-equatorial flow that drives the southwest monsoon. The convergence zone is no longer evident in the wind field. The Somali jet, which develops in this time frame, increases the wind speeds in the Arabian Sea. At the end of the southwest monsoon, as the transition towards the northeast monsoon begins, the south Indian Ocean high weakens and shifts east. The Somali jet disappears and northeasterly winds begin to flow. The ET begins to move south again.

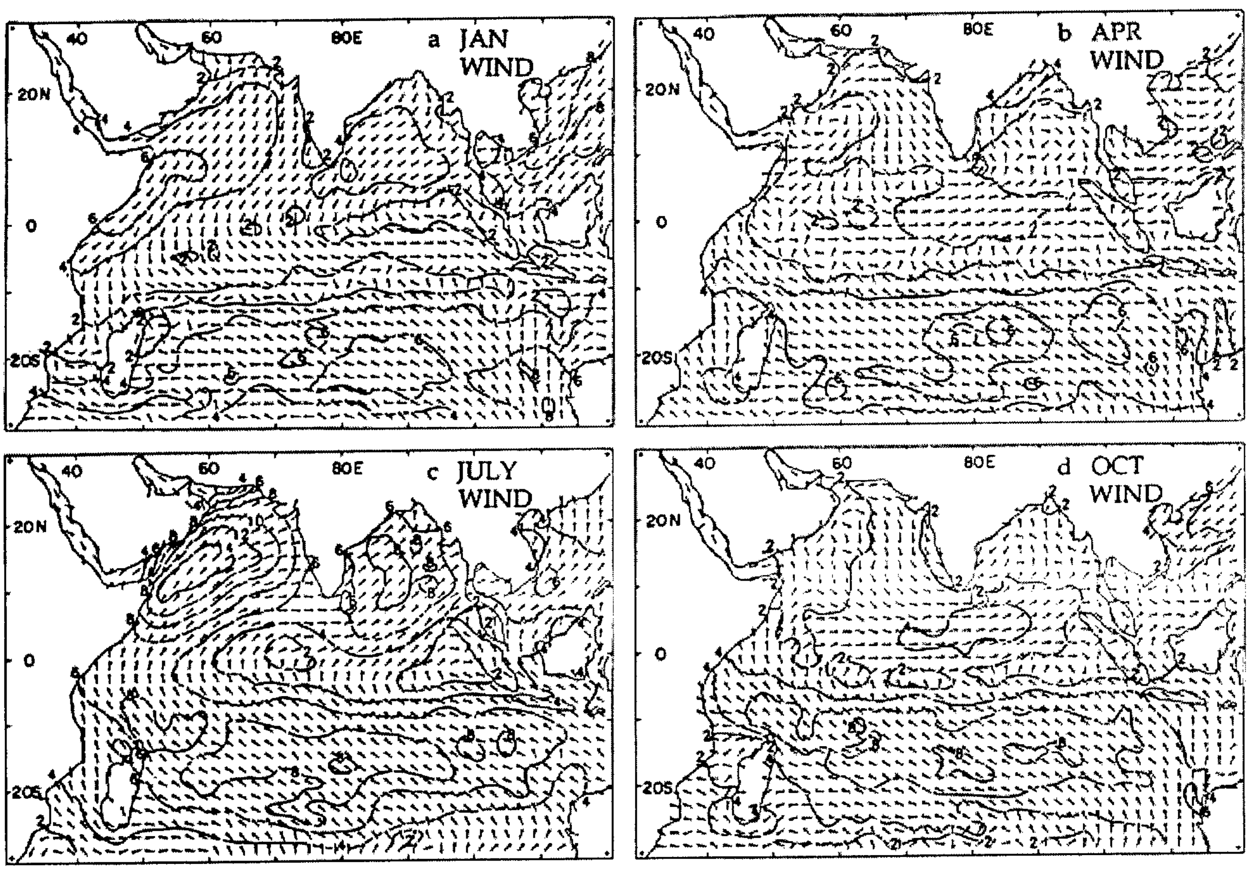


Figure 2-5. Indian Ocean Surface Wind Field . The isotachs have a 2 m/s spacing. (Hastenrath, 1991)

Mid- And Upper-Wind Flow Patterns. The Tibetan Plateau splits the mid-level flow over the northern portion of the region (see Figures 2-6a-d). The winds are weaker south of the plateau. In January, at the height of the northeast monsoon, anticyclones are prominent over the North Indian Ocean at 850 mb, and there is weak ridging at 700 mb. In the upper-levels, strong westerly winds are present over and just to the south of the plateau. The winds decrease as one moves further south over the region.

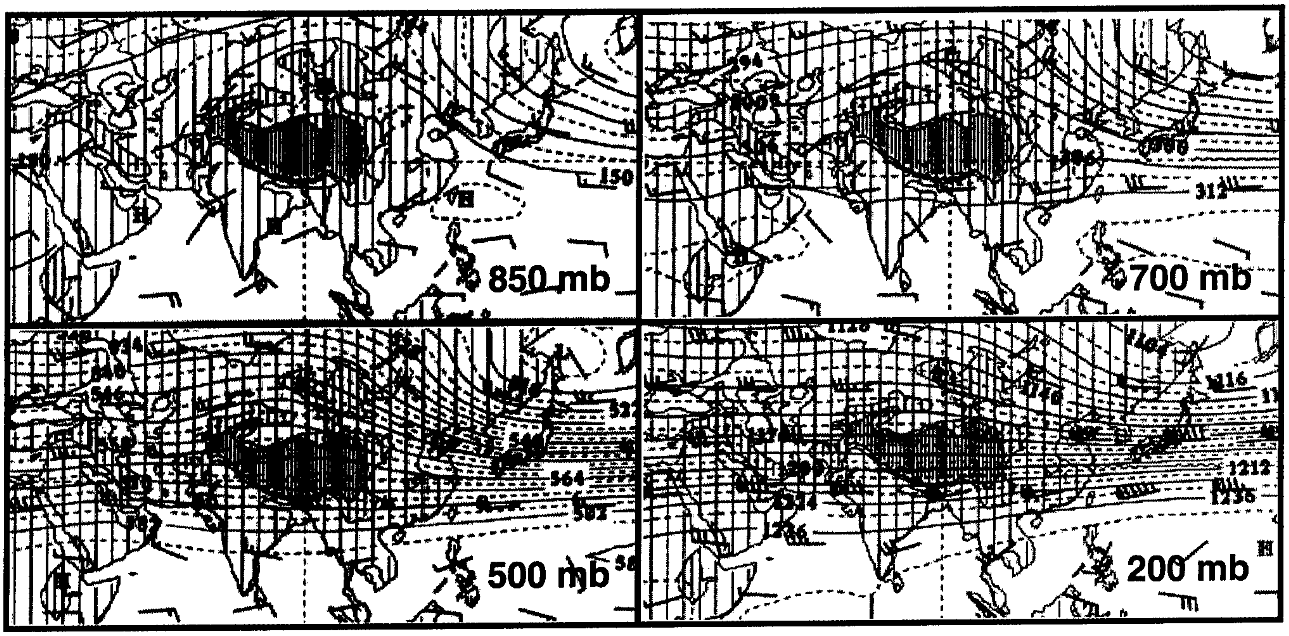


Figure 2-6a. Mean Mid- and Upper-Airflow Patterns—January. (Adapted from NAVAIR 50-1C-1/AWSTR-89/001, Vol. 1, 1989)

As the transition to the southwest monsoon begins, the April flow patterns are weak at all levels. This is particularly true in the lower levels as the ET migrates north.

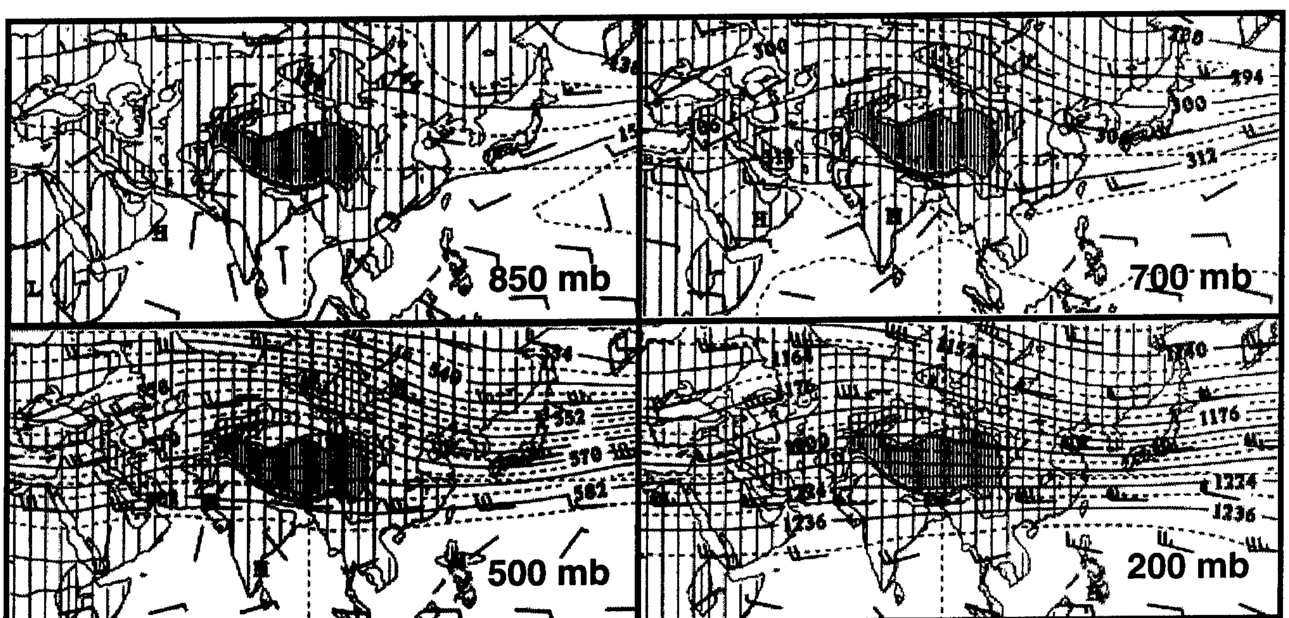


Figure 2-6b. Mean Mid- and Upper-Airflow Patterns—April. (Adapted from NAVAIR 50-1C-4/AWSTR-89/004, Vol. 4, 1989)

Semipermanent Climate Controls

July's 500-mb pattern is complex because 500 mb is the transition level between the low-level southwest monsoon and the 200-mb tropical easterly jet (TEJ). The presence of a low over India indicates weak, indeterminate flow. Meanwhile, the upper-level Tibetan anticyclone establishes itself over the region.

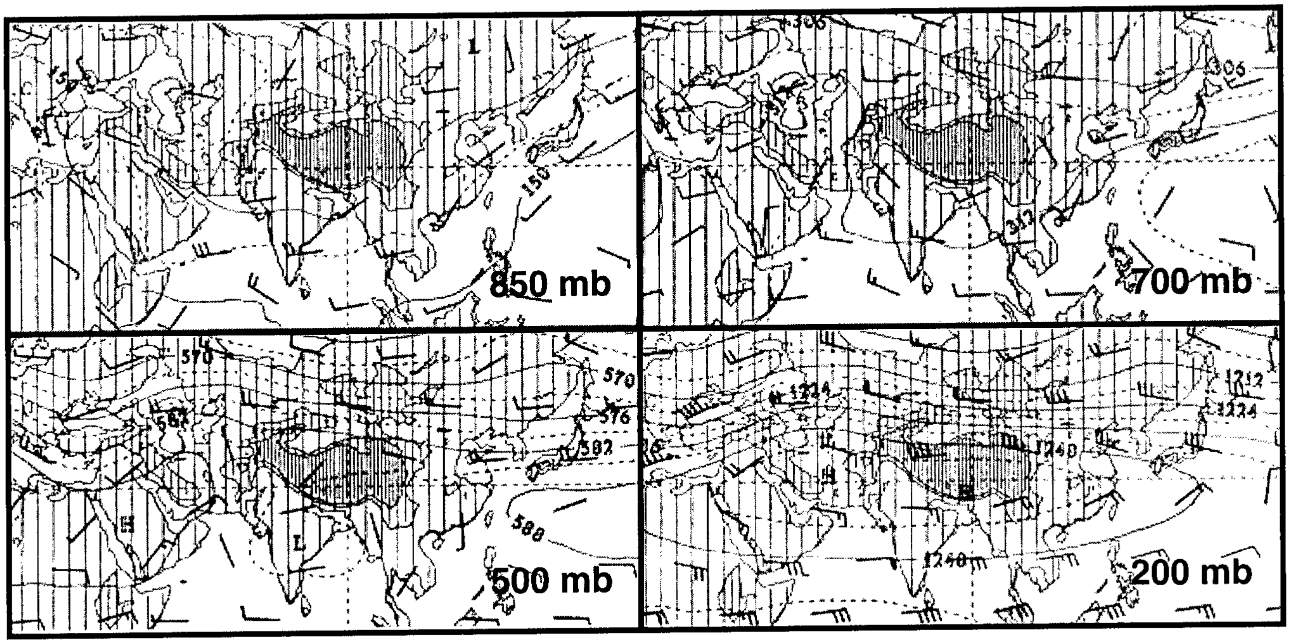


Figure 2-6c. Mean Mid- and Upper-Airflow Patterns—July. (Adapted from NAVAIR 50-1C-7/AWSTR-89/007, Vol. 7, 1989)

By October, the transition to the northeast monsoon is well underway. The flow patterns are weak once again as the ET migrates south. An 850-mb thermal low forms over the Bay of Bengal though it disappears by November. In the upper-levels, the Tibetan high and the TEJ disappear, and the westerly winds migrate south.

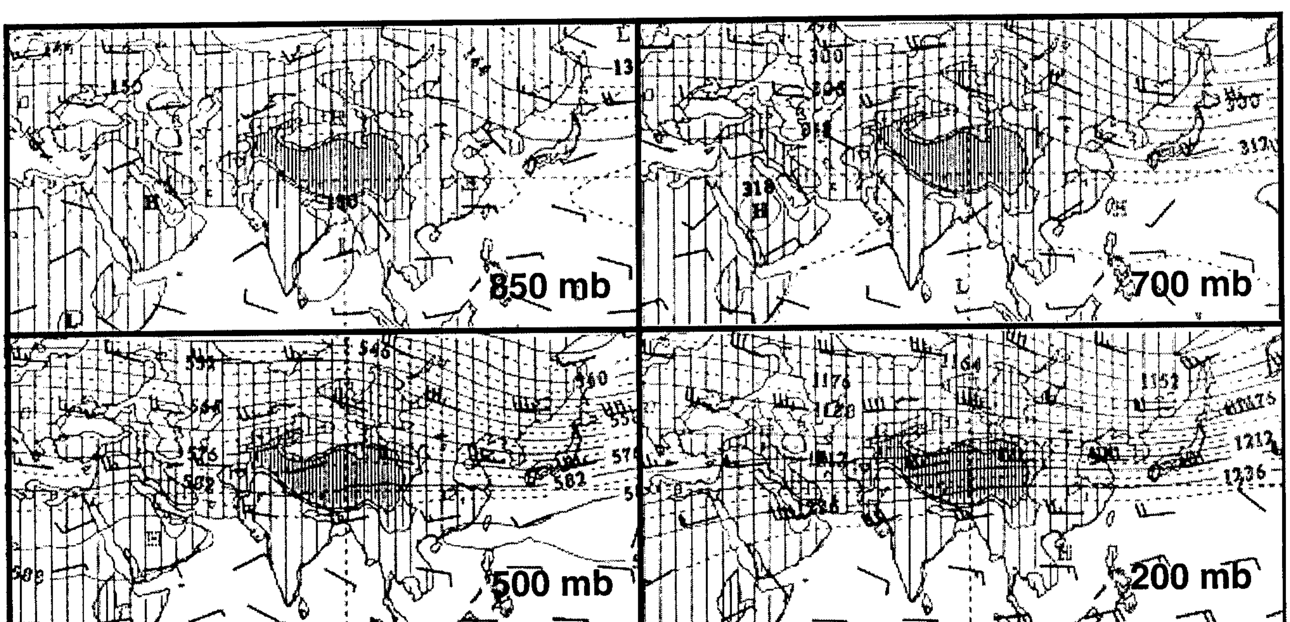


Figure 2-6d. Mean Mid- and Upper-Airflow Patterns—October. (Adapted from NAVAIR 50-1C-10/AWSTR-89/010, Vol. 10, 1989)

Subtropical Ridge. This upper-level feature (see Figures 2-6a-d) has a mean annual position near 15° N, centered at about 130° E. The western perimeter of the ridge extends into the Indian Ocean. The ridge moves north and south with the sun and reaches its southernmost position in January. It provides outflow for convection from the equatorial trough and tropical cyclones. During the southwest monsoon, the Tibetan anticyclone dominates the subtropical ridge over the Indian Ocean.

Tibetan Anticyclone. This upper-level feature develops in April when a high-pressure cell over southeast Asia migrates northwestward to the Tibetan Plateau. Figure 2-7 shows its mean position in May and July. At the plateau's surface (about 600 mb), a heat low forms and is surrounded by a ring of highs along the plateau's mountainous rim. The thermal low is sustained and deepened by the intense heating of the plateau. As it strengthens, so does the anticyclone above it. The anticyclone also interacts with the subtropical ridge aloft. This interaction causes the Tibetan anticyclone's position to vary; if it shifts eastward of 90° E, severe drought results over much of the subcontinent.

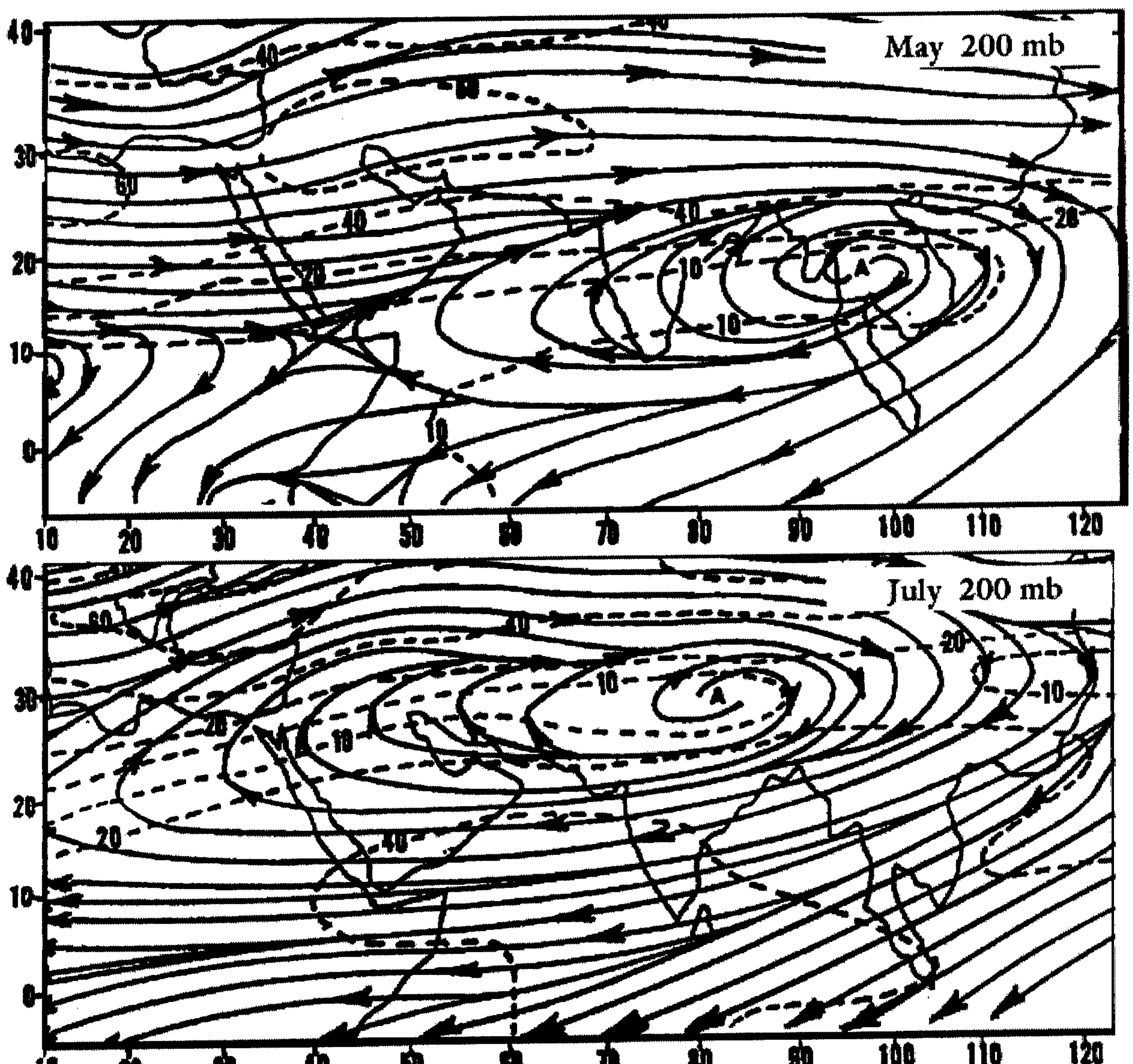


Figure 2-7. Mean May and July Positions of the Tibetan Anticyclone. The figure shows the migration of the Tibetan Anticyclone as it strengthens. (Higdon, et al, 1997 from Chenglan, 1987)

Semipermanent Climate Controls

The Tibetan anticyclone intensifies the easterlies to the south and provides the upper-level divergence important for southwest monsoon rains. Its northeastward movement helps establish the southwest monsoon. Figure 2-8 shows an example of this process. The numbers represent 5-day periods that began 16 April and ended 4 July 1979. The abrupt northward jump between Periods 5 and 6 (11-15 May) coincides with the onset of the southwest monsoon. The Tibetan anticyclone is established over the Tibetan Plateau during period 14 (20-25 June). After period 14, the anticyclone splits. One portion goes west and the other goes east. By period 16, the anticyclone has clearly broken into two cells, one in central China and the other well to the west. The number 15 (not shown in Figure 2-8) is the western cell, while number 16 is the China cell.

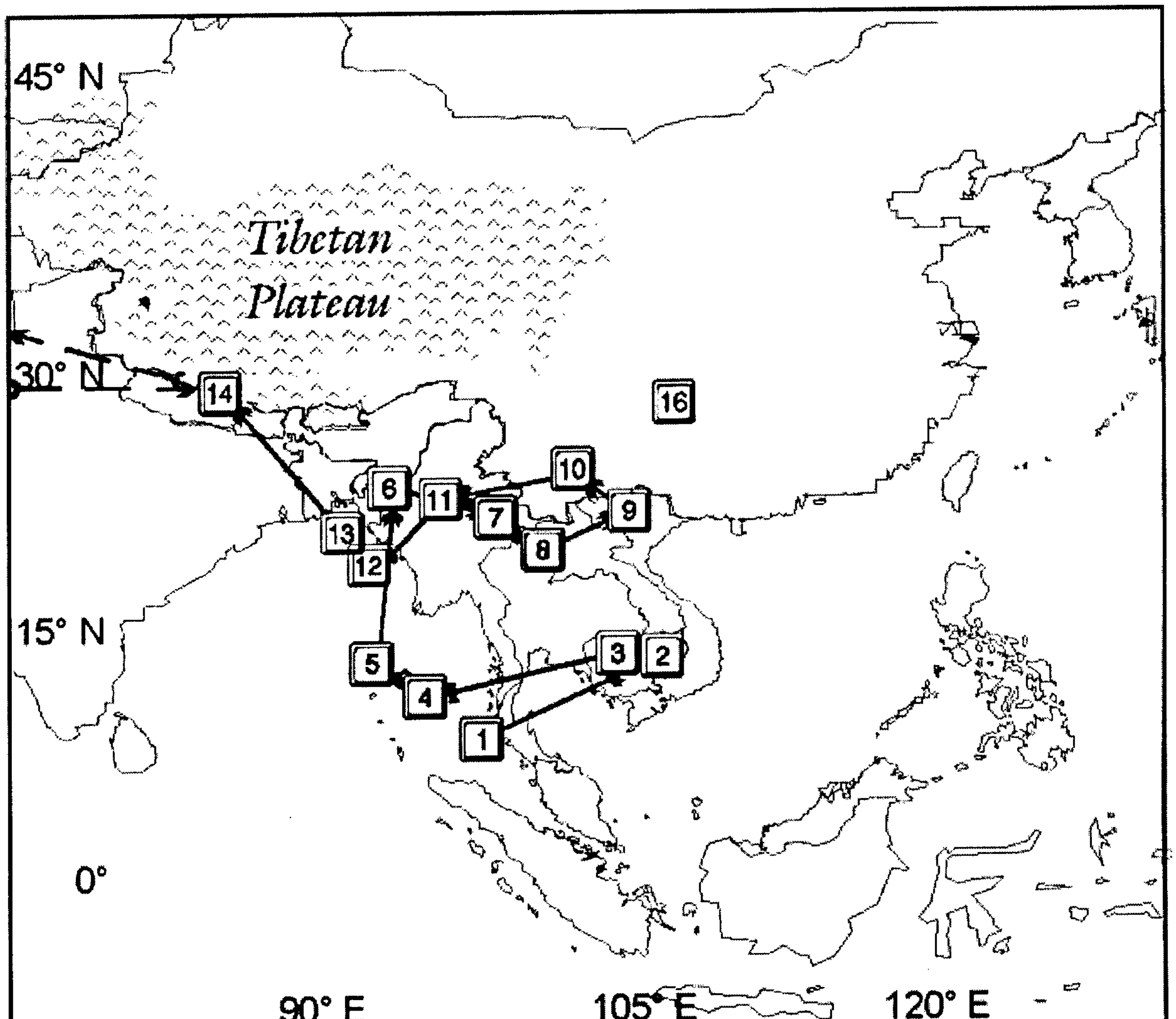


Figure 2-8. Mean Positions of the Tibetan Anticyclone at 200 mb. See text for meaning of the numbers. (Traxler, et al, 1997 from He, et al, 1987)

Jet Streams. Three primary jet types affect this region: the subtropical jet (STJ), the tropical easterly jet (TEJ), and tropical low-level jets.

Subtropical Jet (STJ). This is the southerly branch of the mid-latitude westerlies. (The northerly branch, the polar jet, rarely affects South Asia directly.) During the southwest monsoon, the STJ is relatively weak and lies north of the Tibetan Plateau. As the seasons transition into the northeast monsoon, the STJ intensifies and moves south of the plateau. Figure 2-9 shows the STJ's mean position during January, April, July, and October. The mean height of the STJ is near 39,000 feet; its mean speed is 75 knots in January and 50 knots in July. The STJ provides upper-level steering, shear, and outflow. Rainfall is often concentrated along the jet axis. Although the STJ shows less variability in its daily position, its seasonal variability is great. By the end of May, the westerlies retreat north of the Tibetan Plateau—a prerequisite for the start of the southwest monsoon. Deformation of the wind flow around the mountains creates a distinct pattern during the southwest monsoon with a trough that shifts from the Bay of Bengal to the Arabian Sea.

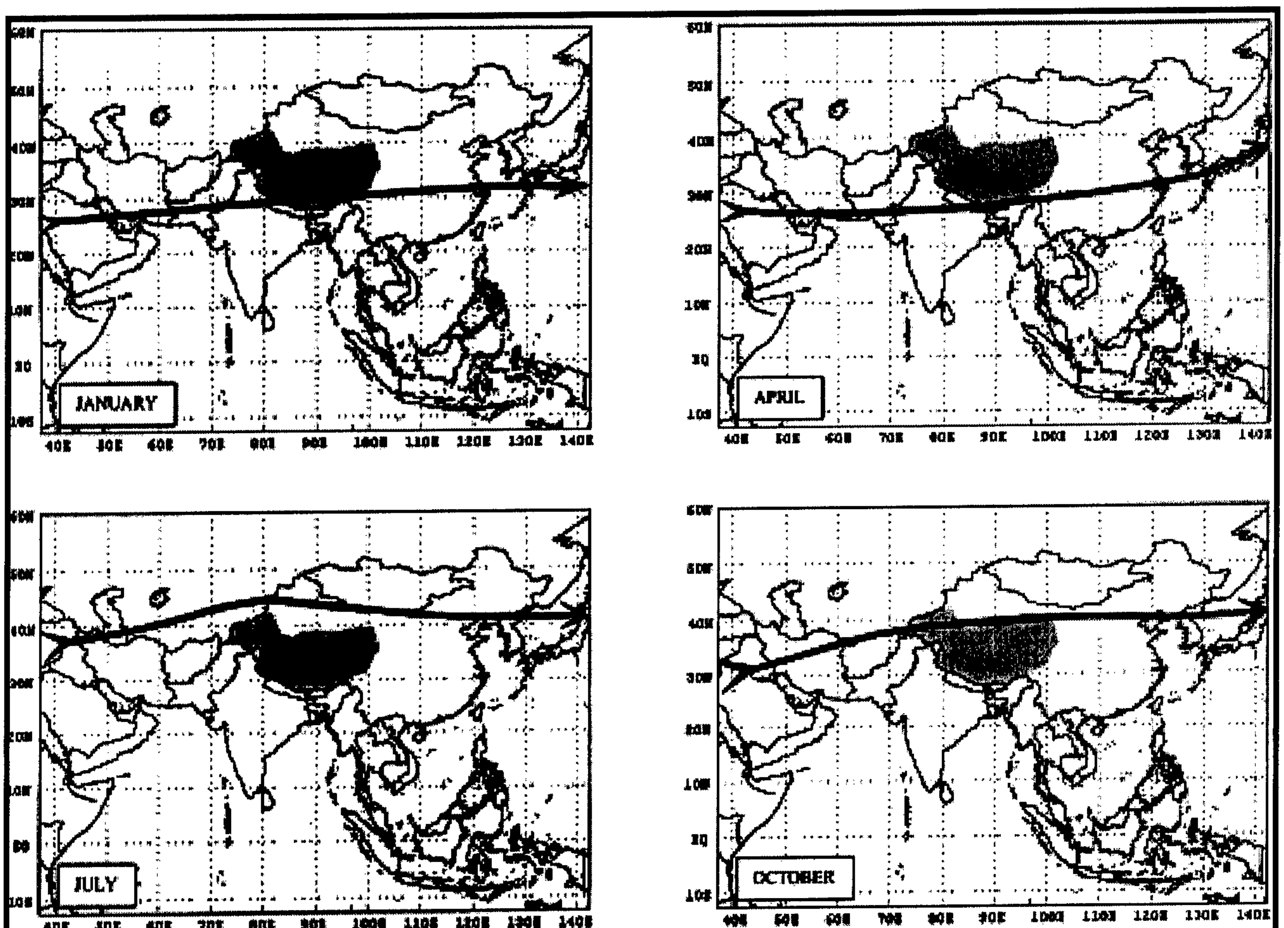


Figure 2-9. Mean Subtropical Jet Stream Positions. The figure shows the mean postion of the subtropical jetstream during each of the seasons. (Traxler, et al, 1997 adapted from Marcal, 1968)

Tropical Easterly Jet (TEJ). This Northern Hemisphere summer jet in the upper-level easterlies develops at or above 200 mb as outflow from the southern edges of the Tibetan anticyclone. Its entrance region lies from over the South China Sea to the western Pacific as far east as Guam (about 140° E). This jet is strengthened over South Asia by the strong temperature contrast between the warm land mass and the relatively cool equatorial water. The TEJ is limited to the southwest monsoon and exists from late June into early September. The mean axis position is near 15° N, 4-5 degrees south of the surface equatorial trough, but it oscillates between 5° and 20° N (see Figure 2-10). The strongest winds are between 73° and 80° E where maximum speeds reach 90 knots; the mean wind speed is 60 knots.

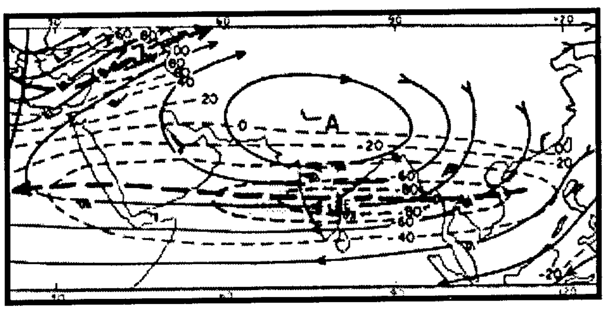


Figure 2-10. Analysis of Tropical Easterly Jet at the 200-mb Level on 25 July 1955. Streamlines are represented by the solid lines, while isotachs (knots) are depicted by dashed lines. JW = westerly jet maximum, JE=easterly jet maximum, A=anticyclone, C=cyclones. Heavy dashed lines with arrows indicate positions of jet axis. (McGregor and Nieuwolt, 1997 adapted from Koteswaran, 1958)

The jet follows the highest sea-surface temperatures. Since a cool area often develops in the South China Sea north of Borneo, the TEJ sometimes splits into two axes near 5° and 20° N (see Figure 2-11). The northern branch is stronger. The TEJ's position and intensity significantly affect the southwest monsoon rains and low-level trade winds. Fluctuations in the TEJ's strength are connected to "pulses" in the monsoon flow. The TEJ also provides an outflow mechanism for ET convection and for convection with the India-Myanmar trough. It causes upper-level divergence in the northern Bay of Bengal directly over the convergence provided by the ET. This triggers monsoon depression development.

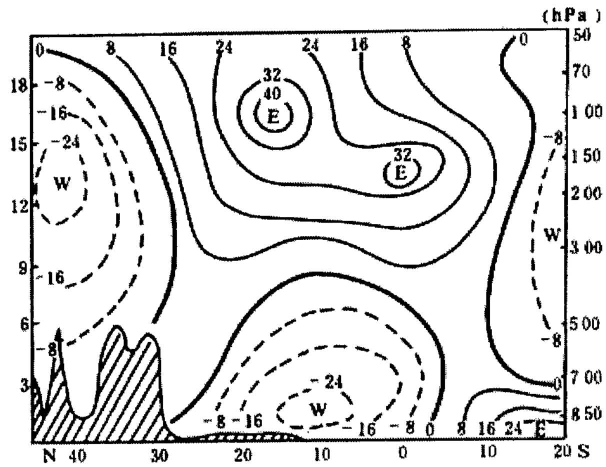


Figure 2-11. Cross-Section of the Mean Zonal Component along 80° E for July. Solid (dashed) lines denotes isotach of easterly wind (westerly wind) in m/s. (Higdon, et al, 1997 from Yihui, 1994)

Tropical Low-Level Jets. Two north-flowing, low-level jets form over the Indian Ocean between February and October. Figure 2-12 shows their locations. The entrance regions for both jets are over warm seas. One jet develops in the Bay of Bengal near the equator near 90° E. It flows northeastward over the northwest Myanmar coast. The second, the Somali jet (also known as the East African jet), is the stronger of the two.

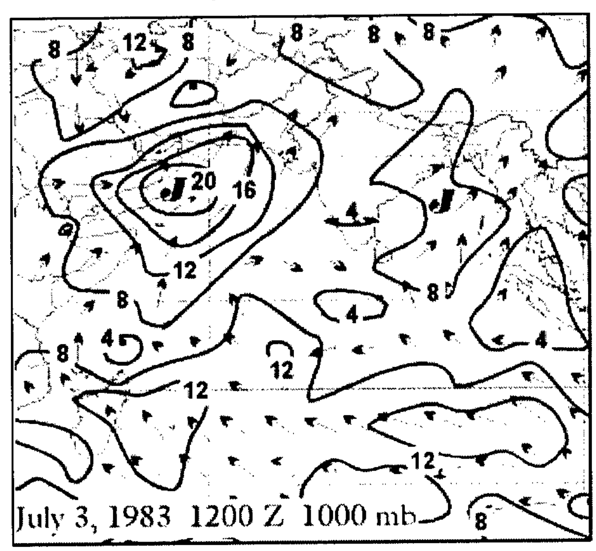


Figure 2-12. Mean Positions of Low-Level Jets. The Isotachs (knots) and arrows show mean flow. The large "Js" show jet core positions. (Traxler, et al, 1997 adapted from Zhou, et al, 1990)

It is active from February to late October (see Figure 2-13), when flow from the South Indian Ocean high is compressed into a high-speed jet core along the eastern edge of Africa. The core normally passes just north of Madagascar heading to the northwest and turns to the northeast across Somalia. The mean core is usually at 2,000 feet MSL over the Indian Ocean.

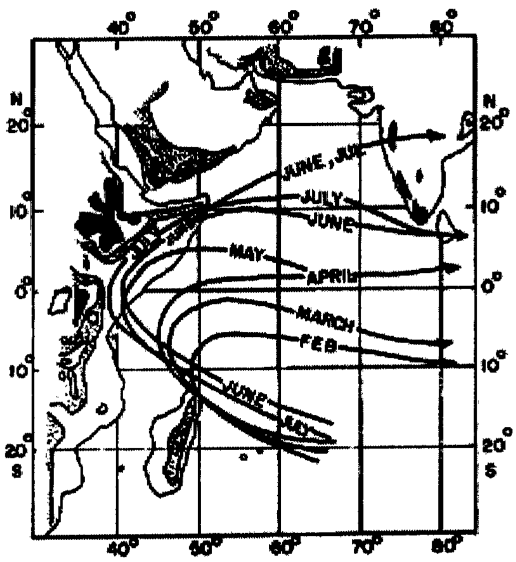


Figure 2-13. Monthly Progression of the Axis of the Somali Jet. (Hastenrath, 1988 adapted from Findlater, 1971)

Figure 2-14 shows the mean July monthly airflow at 3,000 feet MSL across the western Indian Ocean basin.

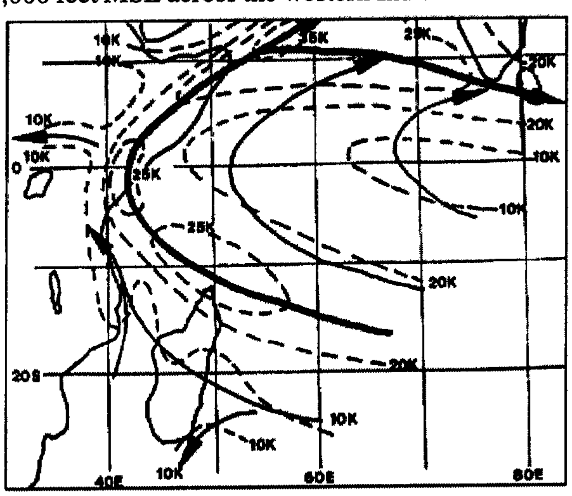


Figure 2-14. July Mean Monthly Airflow at 3,000 feet (900 meters). Solid lines are streamlines; dashed lines are isotachs in knots. (Vojtesak, et al, 1992 adapted from Findlater, 1971)

The Somali jet has mean core speeds of 25-40 knots. This jet first appears in February. It normally strengthens from April to July, then weakens from August to October. Highest speeds are near the equator across Kenya and Somalia, where speeds of 100 knots have been reported. These extreme speeds may be related to Southern Hemisphere cold surges. Like most low-level jets, the Somali jet shows a marked diurnal variation. Peak core speeds occur near dawn, and minimum core speeds occur in late afternoon. Surface speeds beneath the core are the opposite. The minimum speeds occur at dawn, maximum speeds occur in mid-afternoon. The Somali jet is one component of the southwest monsoon as it drives the equatorial westerlies. Fluctuations in its strength appear to be linked to surges in the monsoon flow.

Monsoon Climate. During Northern Hemisphere winter, the warm oceanic ridge and the Asiatic high combine to form a continuous belt of high pressure. In summer, heat lows replace the Asiatic high. This seasonal reversal of the pressure gradient gives rise to the northeast and southwest monsoons that affect South Asia (see Figure 2-15). The term "monsoon," from the Arabic "mawsim" or "season," is commonly applied to those areas of the world where there is a seasonal reversal of prevailing winds. The accepted definition of a monsoon climate is based on the following criteria:

- Prevailing wind direction shifts by at least 120° between January and July.
- The average frequency of prevailing wind directions in January and July exceeds 40 percent.
- The mean resultant wind in at least one of the months exceeds 6 knots.
- Fewer than one cyclone-anticyclone alternation occurs every 2 years in either month in a 250 x 250 NM (500 x 500 km) square.

Equatorial Trough (ET). Also called the monsoon trough, intertropical convergence zone (ITCZ) or near-equatorial trough (NET) for the South Asia region by various authors, the ET marks a zone of wind discontinuity with horizontal velocity convergence and upward vertical motion. There is cloudiness along and near this zone, aligned in nearly an east-west direction.

Semipermanent Climate Controls

The ET oscillates north-south with the sun. In the Indian Ocean, the ET separates the westerlies in the near-equatorial region and the easterly trade winds on the other side of it. The westerlies are largely the southeast trades (source south Indian Ocean high) that deflect eastward after crossing the equator.

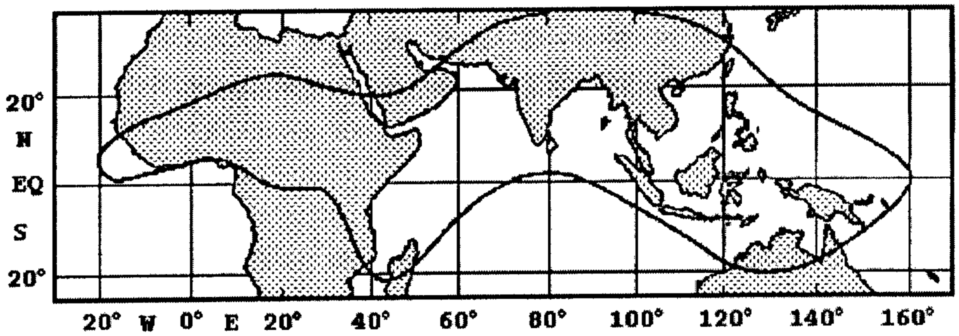


Figure 2-15. Monsoon Region. Area satisfying Ramage's monsoon criteria is enclosed by the solid line. (Adapted from Ramage, 1995)

Source regions for the easterly trades are the North Pacific high and the Australian high during the summer, and the Asiatic high in the winter. See Figure 2-16 for the positions of the ET in January and July.

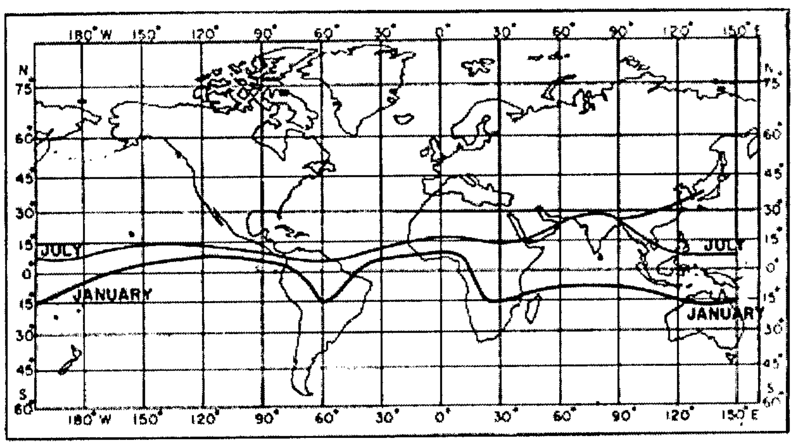


Figure 2-16. Surface Positions of the Equatorial Trough (ET) in January and July. (Asnani, 1993)

Movement. The ET's annual movement lags behind the sun by nearly two months (Figure 2-17). The highest temperatures occur about a month after solstice over the large continental areas, and nearly two months later over the oceans and in the upper air. During its annual oscillation, the ET migrates farthest from the equator into the summer continental regions.

Structure. Tropical maritime air is found on the equatorial side of the ET. The air on the poleward side comes from the higher latitudes. It undergoes much subsidence and is still relatively warm, dry and stable. It is also warmer than the tropical maritime air on the equatorial side. Because the ET in the Indian Ocean and surrounding lands is a region of low pressure, it slopes upward towards cooler air. Thus, the vertical slope of the ET is generally towards the equator. The slopes are not uniform with height; they fluctuate with small changes in density and wind speed. Figure 2-18 shows the approximate positions of the ET's various levels for January and July. The equatorial trough is deepest over India during the southwest monsoon, where it can be located up to the 400-mb level on upper-air charts. Elsewhere, it is generally located only up to the 700-mb level.

Associated Weather. The height and slope of the ET are the main factors in the distribution of weather around it. The slope is highly variable in space and time; its height ranges from 6,500 to 33,000 feet. Relative cool, moist air is on the equatorial side with relatively dry, warm, and stable air on the poleward side. Broad bands of

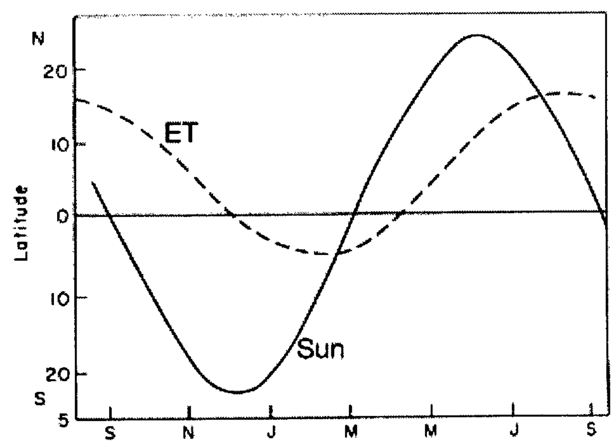


Figure 2-17. Annual Movement of Sun's Zenith Position Versus the ET. (Riehl, 1979)

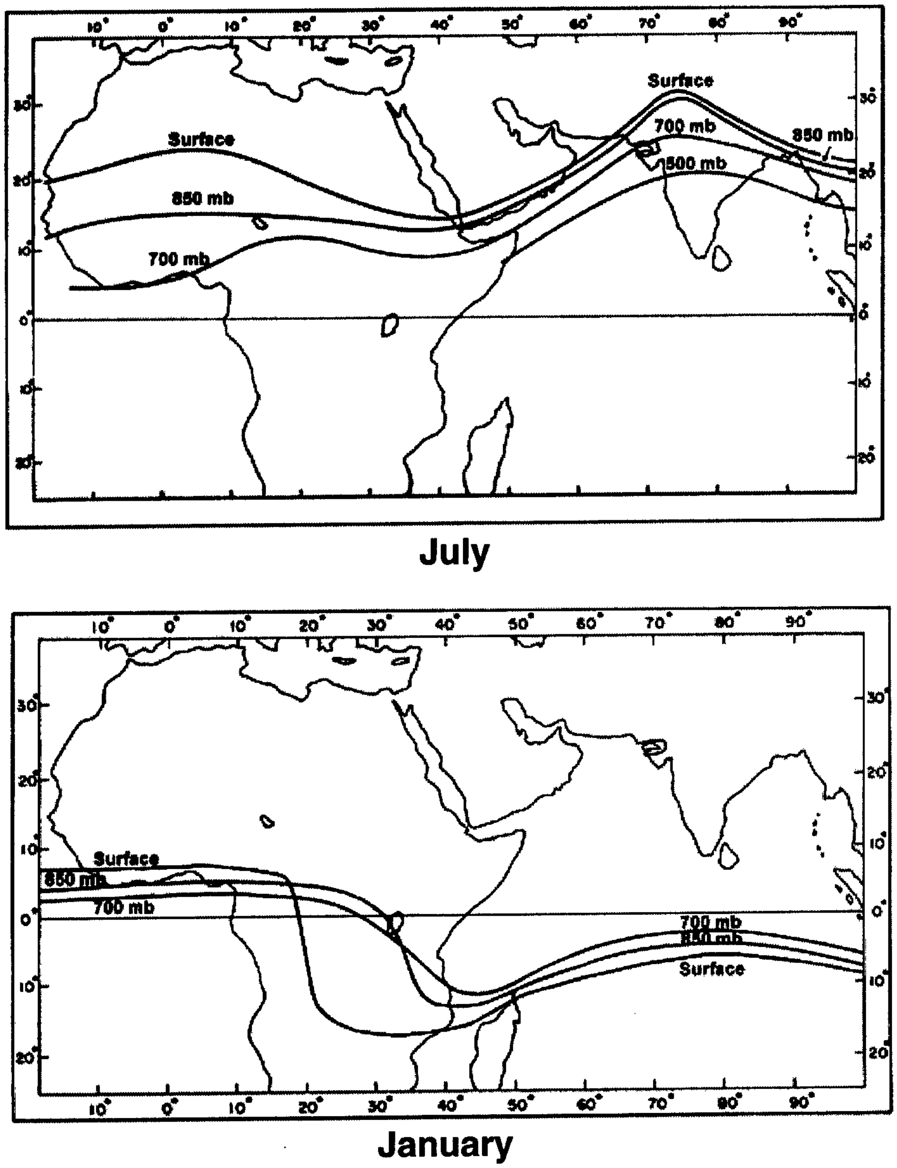


Figure 2-18. Equatorial Trough (ET) Slope for January and July. Depicts the climatological mean surface, 850 mb and 700 mb positions of the ET. (Asnani, 1993)

relatively dry, easterly winds flow above the ET discontinuity out of the subtropical anticyclones. Clouds form in the moist layer on the equatorial side. Large cumuliform formations are possible if the moist layer is more than 10,000 feet deep. Vigorous thunderstorm activity and heavy precipitation occur within these formations. The rest of the area may get shallow cumulus or stratocumulus. This results in the maximum cloudiness being found 125-300 miles (200-500 km) on the equatorial side of the ET's surface position.

When associating weather with the ET, the following points apply:

- If the underlying moist layer is shallow, as over a desert region, there may be no rainfall.

- The ET is not a long, unbroken band of heavy cloudiness. It consists of cloud-clusters separated by large cloud-free regions. Each cloud cluster has mesoscale circulations that create lines of clouds separated by cloud-free zones. This is due to the

movement of synoptic-scale tropical waves in the vicinity of the ET.

- The ET is not a static zone with steady-state conditions of cloudiness. There are oscillations in the position and intensity of vertical movement in the region. There are also oscillations, influenced by land-sea breezes, with a period of one day. Migratory tropical and extra-tropical waves can cause oscillations with periods up to 4-5 days. Oscillations with larger periods are associated with the position and intensity of planetary-scale features like the Hadley cell.

Northeast Monsoon. The Asiatic high dominates the Asian continent during the Northern Hemisphere winter months. As a result, the pressure over Asia decreases rapidly southward towards the ET, which is south of the equator. South of the Himalayas, the pressure gradient is weak and results in a northerly wind flow across the Indian subcontinent. The Himalayas prevent the direct movement of arctic air into South Asia. Instead, modified air moves into the Indian subcontinent indirectly. One route is from the northwest across the mountains of Pakistan. It is also channeled into the region from the east around the southern periphery of the plateau. The region also receives air from the southern slopes of the Himalayas. It is possible the winter circulation is fed, in part, by subsiding air over the northern part of the subcontinent. In any case, the resulting circulation is a fairly weak, dry northerly air flow. Little rainfall occurs over most of the region and the skies are generally clear.

Southwest Monsoon. This season is at full strength between June and September. Rainfall over northwestern India begins in late May or early June and ends in early to mid-September. Most locations receive 75-90 percent of their annual rainfall during it. The southwest monsoon develops in response to the northward movement of the western Pacific Ocean's subtropical high-pressure ridge. The process begins in April. As the subtropical ridge moves northward and strengthens, changes in the general circulation pattern take place. The Asiatic low replaces the Asiatic high. The subtropical westerly jet moves north of the Tibetan Plateau and gradually decreases in intensity. The Tibetan anticyclone moves over the plateau. The TEJ sets up south of the Himalayas. In the meantime, the equatorial trough begins its northward movement into the north Indian Ocean while the Somali jet establishes itself in the western Indian Ocean. All of this activity results in cross-equatorial flow that allows the air stream from the south Indian Ocean high to reach the Himalayas. These southerly winds reach peak intensity and farthest north in July and August then retreat southward in September (see Figure 2-19).

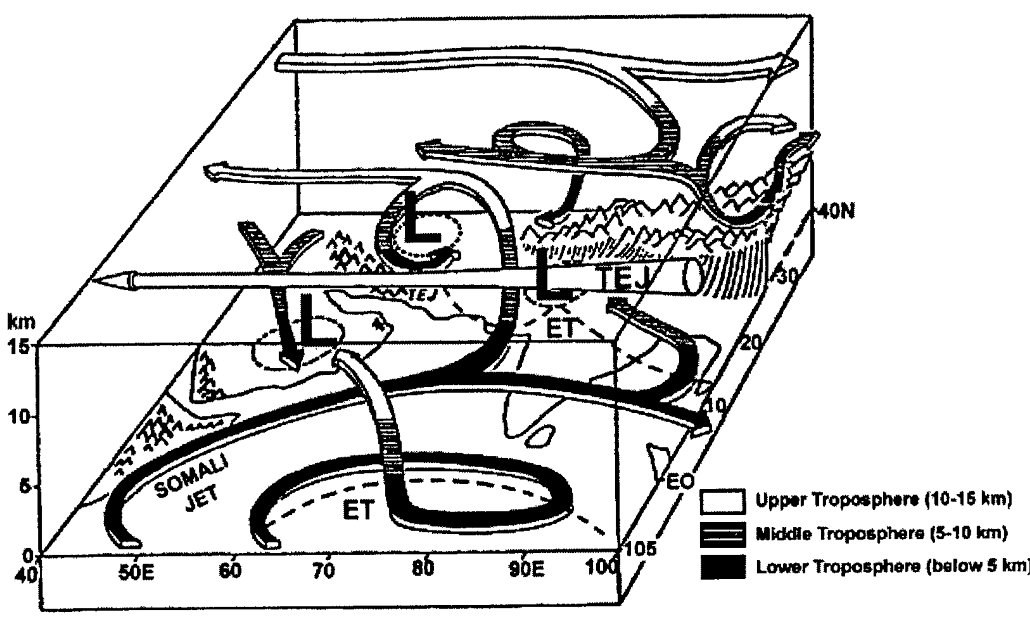


Figure 2-19. Southwest Monsoon Circulation over the Indian Ocean. (Schematic adapted for use by by Air Weather Service, 1998. Original source unknown.)

The monsoonal wind flow brings west to southwest flow of maritime tropical air to the Indian subcontinent. The transport of air into the northern hemisphere occurs across a line from a point near eastern Africa to a point just west of Sumatra. This airmass often attains considerable depth, from the earth's surface to 20,000 feet. This air is quite humid; its relative humidity rarely falls below 70 percent. During July and August, the relative humidity is generally more than 80 percent throughout the airmass. Consequently, the temperature lapse rate is always near the moist adiabatic, which leads to intense thunderstorm activity. Afternoon thunderstorms over land areas are the rule.

Controlling Mechanisms. Several features maintain, control, and regulate monsoon circulation. Differential heating, coriolis force, and condensation or evaporation of water vapor trigger the monsoon.

• Differential heating. This arises from the differing responses of ocean and land to solar radiation. Since water has a higher heat capacity than dry soil, its specific heat is larger and it can distribute heat through a greater depth by mixing. As a result, the annual cycle of the water's surface temperature has a smaller amplitude than land temperature. It also lags behind solar heating by about two months. Air in contact with the surface can gain solar energy absorbed by that surface and convect heat upward. As a result, differential heating leads to a large reduction of atmospheric pressure over land. This is especially true over the Indian subcontinent in Northern Hemisphere spring. The pressure difference created is minimized by a nearly horizontal flow of cooler, denser air from the ocean. As cooler air sinks, it forces warmer air over the land upward. This initiates a circulation in a vertical plane, whose lower arm constitutes the familiar monsoon winds.

• Coriolis deflection. The earth's rotation strongly influences monsoonal circulation. It deflects the winds towards the right in the Northern Hemisphere and towards the left in the Southern Hemisphere. Magnitude of deflection is a function of latitude.

• Condensation or evaporation of water vapor. Evaporation/condensation is another mechanism of the southwest monsoon. The Indian Ocean water forms a vast reservoir of stored solar energy. Some of the energy is lost to evaporation. The energy enters the atmosphere when water vapor condenses. In a monsoon environment, this occurs in air that moves toward or over land as it ascends. The heat adds additional buoyancy to that provided by the underlying surface. This favors further ascent and provides a stronger inflow of moist air at the lower levels from ocean to land. Since air holds more water vapor at higher temperatures, this moisture transport tends to be greatest in late summer when the sea surface and air temperatures are at their highest. Thus, the southwest monsoon circulation is strongest in the late summer. Uninhibited development of the monsoon circulation is prevented by the clouds that develop in ascending air. The clouds limit the solar radiation received at the surface.

Development. The development of the southwest monsoon usually begins first over southern China then progresses westward over Southeast Asia. It does not begin over South Asia until more than a month later. The reason for this delay is the upper-air circulation at 20,000-26,000 feet. Westerly winds prevail at this level over the entire area south of the Tibetan plateau during the Northern Hemisphere winter. These conditions are similar to those at the 700-mb level (see Figure 2-20). This circulation pattern induces an upper-level trough over the Bay of Bengal. By late Northern Hemisphere

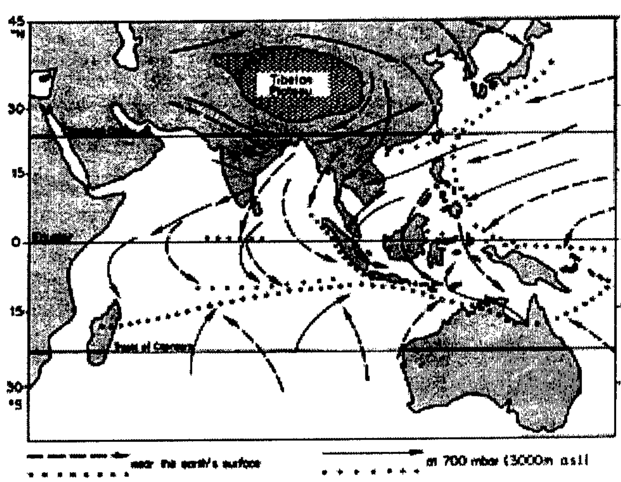


Figure 2-20. Circulation Pattern of the Asian Northeast Monsoon. December to March wind flow patterns are depicted by the arrows while dots represent convergence zones. (McGregor and Nieuwolt, 1998)

spring, this trough aids in the development of upper-level easterlies over southern China and Southeast Asia. The easterlies eventually evolve into the TEJ, which is necessary for the development of the southwest monsoon. They constitute the upper return movement of air towards the equator, which makes them a part of the southwest monsoon circulation (see Figure 2-21).

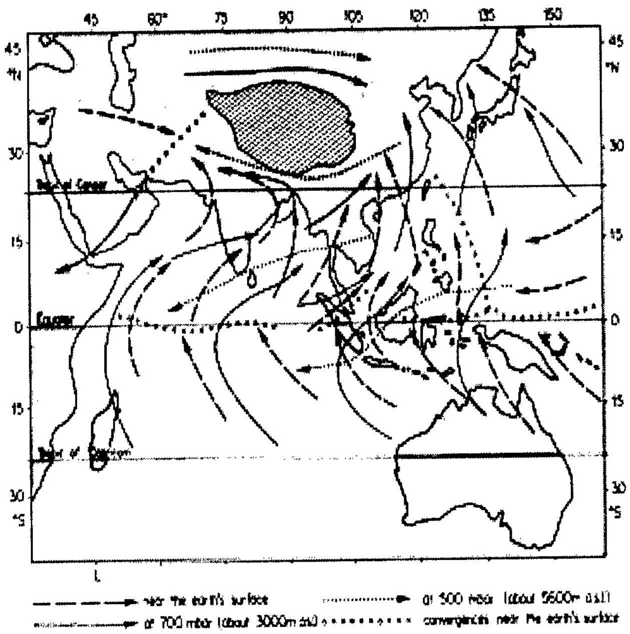


Figure 2-21. Circulation Pattern of the Asian Southwest Monsoon. June to September wind flow patterns are depicted by the arrows while dots represent convergence zones. (McGregor and Nieuwolt, 1998)

Over India, however, prevailing westerlies near 26,000 feet delay the development of the southwest monsoon. By late May, the westerlies suddenly shift north of the Tibetan plateau. This shift allows the upper-air trough to move west and position itself along 75° E. This allows the upper-air easterlies to settle over northern India and opens the way for the southwest monsoon at the lower levels.

Onset. The onset of the southwest monsoon begins the rainy season for South Asia. It starts over the southeastern Bay of Bengal in the middle of May. From there it moves slowly northwestward until it covers all of India by the middle of July (see Figure 2-22). Indian meteorologists make the arrival of the southwest monsoon "official"when it reaches Kerala in southwest India. The arrival of the southwest monsoon varies from as early as 11 May to as late as 18 June. The average date is 2 June with a standard deviation of 8 days. The start of the southwest monsoon over South Asia implies the ET has arrived over the region. It further implies the ET is moving north and will not recede south until its withdrawal. The features associated with the arrival of the southwest monsoon are as follows:

- The westerlies south of the ET are strong, on the order of 20 knots.
- Deep westerlies extend to at least 20,000 feet above sea level.
- The equatorial trough is well-defined on synoptic charts. It sometimes develops a closed low or depression.
- There is heavy rain accompanied by heavy thunderstorms. Rainfall totals along the west coast of India are around 4 inches (102 mm) in 24 hours.

It is difficult to determine monsoon onset and follow its advance through the region. The biggest problem is the monsoon does not advance, remain, or retreat uniformly. It fluctuates greatly in position and intensity when it advances as well as after it establishes itself over a region. As it advances, the monsoon shows all of the

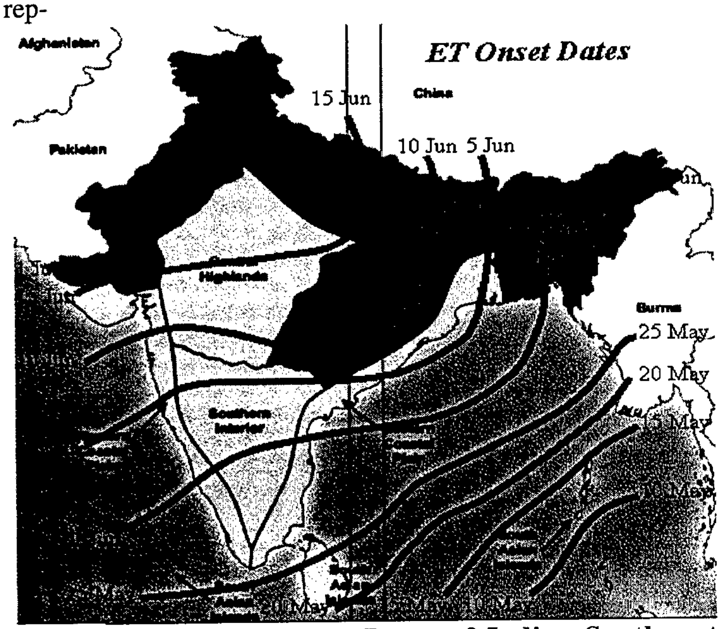


Figure 2-22. Mean Onset Dates of Indian Southwest Monsoon. (Adapted from Hastenrath, 1988 after Das, 1972)

features of the ET listed above at some locations, while at other locations, one or more may be missing. The monsoon will sometimes weaken after it establishes itself. Pre-monsoon flow may return and make it difficult to determine if the monsoon is still there.

Withdrawal. The southwest monsoon loses most of its force by the end of August, especially in the northernmost regions of the subcontinent. The transition to the northeast monsoon circulation is ready to begin. The equatorial trough retreats south as the subtropical ridge re-establishes itself over northwest India. The monsoon withdraws from northern India by early September (see Figure 2-23). Thunderstorm activity is considerable during the withdrawal. Heavy rain and thunderstorms are sometimes referred to as the southwest monsoon's "last kick." Early morning fog after the previous evening's thunderstorm may signal the monsoon's end.

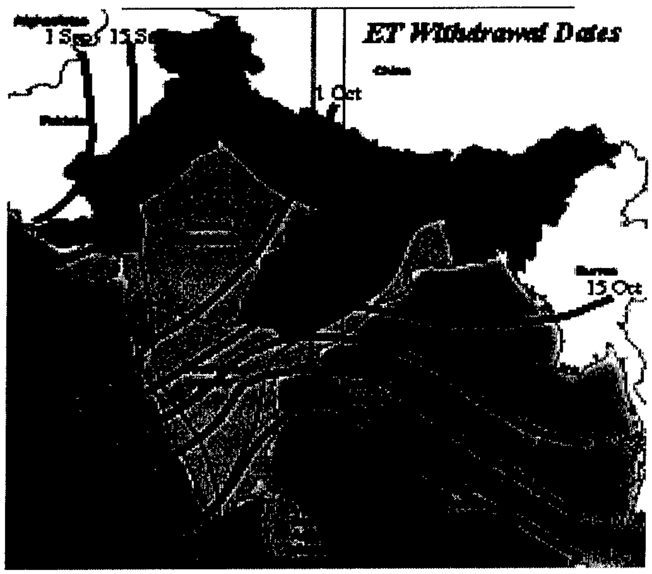


Figure 2-23. Normal Dates of Withdrawl of Southwest Monsoon. (Adapted from Hastenrath, 1988 after Das, 1972)

Onset Vortex. The "onset vortex" is a cyclone associated with the arrival of the southwest monsoon over the Indian Ocean. It normally develops between mid-May and mid-June in the eastern Arabian Sea or the Bay of Bengal. The disturbance resembles, and can become, a tropical cyclone. Formation begins at the mid-tropospheric level, usually at 700 mb, then intensifies downward to the 850-mb level with strong low-level convergence. Strong zonal flow (westerlies produced by the Somali jet) develops before the onset vortex. The disturbances are 200-500 miles (320-800 km) across with a life span of 3-10 days. Surface winds near the storm's eye can reach 50 knots or greater. Researchers differ on the relationship between the onset vortex and the southwest monsoon. Some believe the vortex is a trigger. Other believe it is a response to the southwest monsoon's

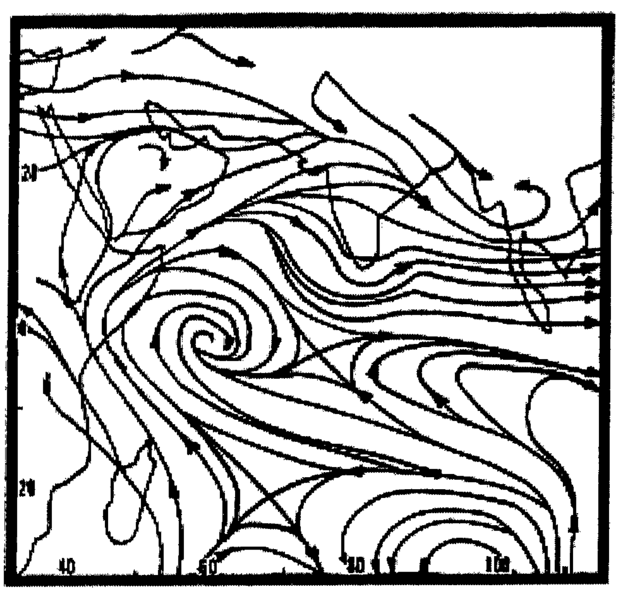


Figure 24a. Streamline Chart (850 mb), 23 May 79/ 1200Z. Depicts low-level flow prior to Onset Vortex. (Krishnamurti, et al, 1981)

Figure 24b. Streamline Chart (850 mb), 17 Jun 79/ 1200Z. Depicts low-level flow during Onset Vortex (C). (Krishnamurti, et al, 1981)

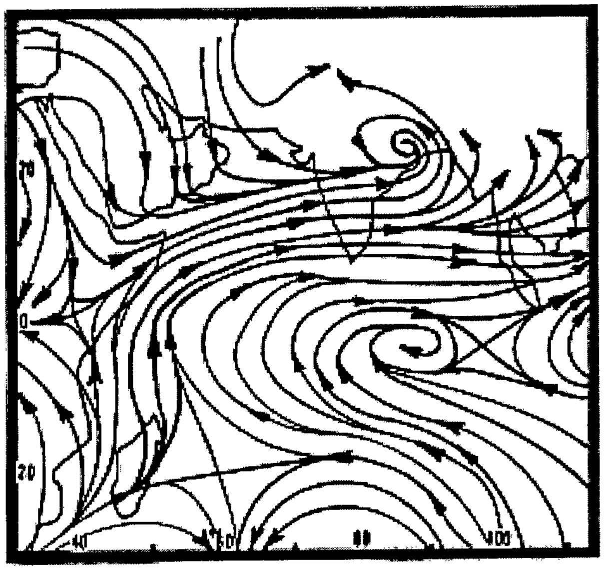


Figure 24c. Streamline Chart (850 mb), 27 Jun 79/ 1200Z. Depicts low-level flow after the Onset Vortex. (Krishnamurti, et al, 1981)

movement towards the Asian land mass. Figure 2-24a-c shows the 850-mb flow before, during, and after the "onset vortex" that developed in 1979.

Monsoon Breaks. The southwest monsoon covers all of India by the end of June. During July and August, the peak intensity period, the monsoon does not maintain uniform or even nearly uniform intensity in terms of rainfall over the country. These variations in rainfall are joined by variations in the synoptic scale weather patterns. When there is low rainfall activity, a "*break*" in the monsoon occurs. Monsoon breaks vary in both intensity and duration. Two of the synoptic situations leading to them involve an ET shift to the north.

- If the western end of the equatorial trough shifts north, a monsoon break is relatively short-lived, about 2-3 days. This occurs when a western disturbance (a low pressure system) moves across the western Himalayas. When it happens, there is excessive rainfall over the western Himalayas and deficit rainfall over the plains of northwest India.

- If the eastern end of the equatorial trough shifts north, a break of 4-5 days is likely. This occurs with the movement of a monsoon depression from the northern Bay of Bengal to Assam. Excessive rain falls in the foothills of the eastern Himalayas and sometimes leads to floods along the rivers of northeast India. At the same time, rain becomes scarce over the plains of Uttar Pradesh, Bihar, Madhya Pradesh, Orissa and Gangetic West Bengal.

Other situations that may lead to a monsoon break include the following:

- Development of a warm temperature anomaly over central India, and a cold temperature anomaly over northwestern India.

- One or two low pressure waves move westward across the south Bay of Bengal, and possibly southern India, in the lower and middle troposphere.

- A ridge appears over central India in the lower troposphere.

- The Tibetan anticyclone weakens and moves northeast.

- Blocking highs develop over north Asia along with mid-latitude troughs that extend to lower than normal latitudes. This leads to a series of lows that may move eastward across extreme northern India.

- Monsoon depressions do not occur over the northern portions of the Bay of Bengal.

- Moisture is confined to very low levels where specific humidity decreases from the bottom to top at a relatively fast rate. Convective instability increases, and rains, if any, tend to be convective in nature.

Even though the above listed features have occurred during a monsoon break, research indicates none are absolute indicators a monsoon break is ready to occur.

Monsoon breaks occur most often in the middle of August although they can occur anytime during July and August. The southwest monsoon can and does weaken during June and September, but these events are not considered to be "breaks." During June, the monsoon may not have totally established itself over the entire region, thus a break is not possible. In September, any weakening of the southwest monsoon is regarded as part of the withdrawal phase. There are more monsoon break days in the middle of August than any other ten-day period, and August breaks last slightly

longer. If the monsoon break has been intense and long, a gradual recovery of the synoptic conditions to a normal pattern occurs. There are two situations that can hasten the recovery:

- A monsoon depression develops over the Bay of Bengal.
- A low-pressure wave moves west across southern India from the Bay of Bengal. This wave intensifies during or after its passage, becomes a low pressure area or depression, and moves north-northwest along India's west coast. In its wake, the pressure gradient builds up to its normal value.

Equatorial Westerlies. This wind band is formed by the outflow of the South Indian Ocean high and is enhanced by the Somali jet. It extends along the north side of the equator from near the African coast eastward to 130° E. In summer, it is strengthened around 110° E by outflow of the Australian high. This westerly flow extends from the surface to 700 mb, but in July, its strongest month, it extends to 500 mb (see Figure 2-11). The equatorial westerlies are a source of cool, subsiding air between the northern and southern monsoon boundaries. East-moving waves form in this flow.

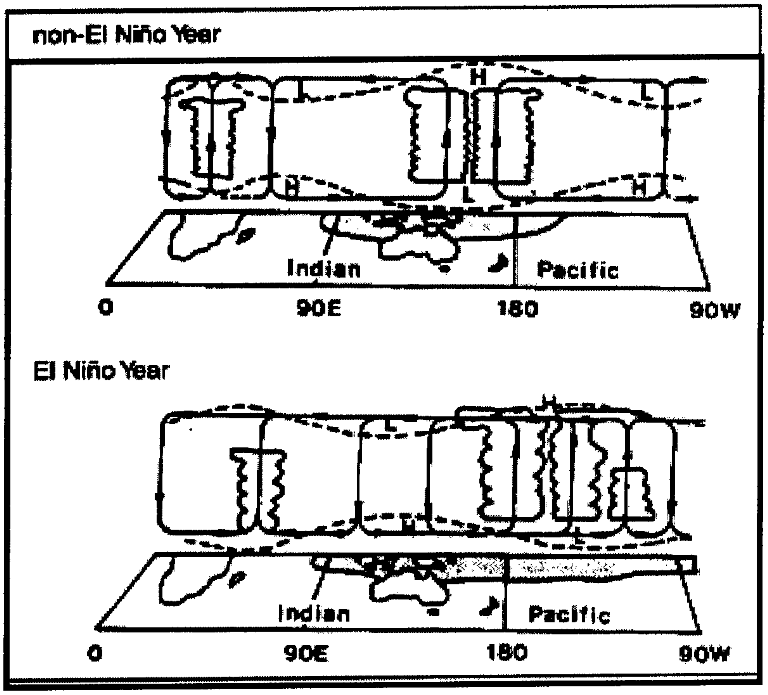


Figure 2-25. Equatorial Circulation Model during El Nino and Non-El Nino Years. Sea-surface temperatures are above 81°F (27°C) in shaded areas. (Fein and Stephens, 1987)

Southern Oscillation (El Niño, La Niña). Also known as the Walker circulation, the southern oscillation is a complex global atmospheric and oceanic phenomenon. It is an important circulation mode of the tropical atmosphere characterized an air exchange between the eastern and western hemispheres. It involves periodic changes in atmospheric pressure, sea-surface temperature, and air temperature. There are two phases to the southern oscillation, a warm "El Niño" and a cold "La Niña," with intervening transitions. The time to complete one cycle varies between 2 and 10 years and averages 3 years. Atmospheric circulation changes that occur near the equator and in association with these phases are shown in Figure 2-25. These changes have significant impact on the climate of the Asian subcontinent.

Figure 2-26 shows the southwest monsoon rainfall totals over India for the period 1871 to 1978. The figure shows the rain amount that falls from June through September. Values outside one standard deviation of the mean are considered significant departures from normal. Severe

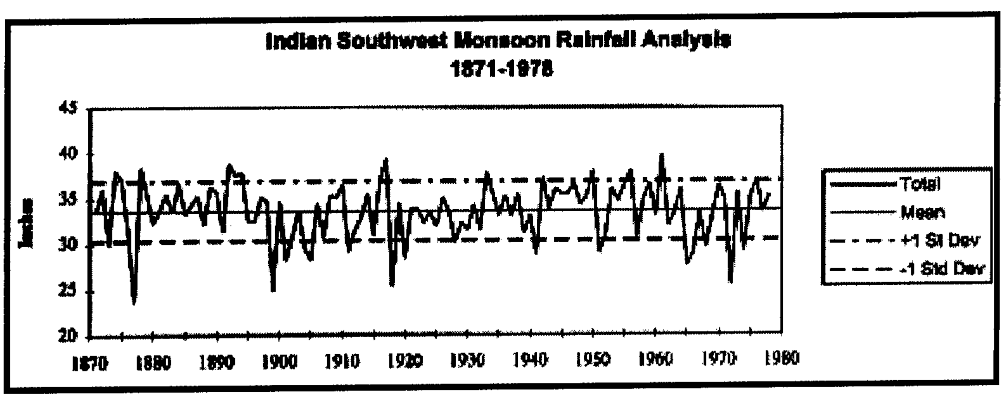


Figure 2-26. Southwest Monsoon Rainfall (June to September) of India. Taken as one unit, these amounts represent 78 percent of annual total. (Pant and Kumar, 1997)

floods or droughts result from these departures. Researchers found a strong relationship between rainfall and the southern oscillation. A high southern oscillation index (SOI) generally led to excessive rain while a low SOI usually resulted in drought. La Niña events are associated with a high SOI, and El Niño events are associated with a low SOI.

Note: The southern oscillation index (SOI) is based on the sea-level pressure difference between Darwin, Australia and the island of Tahiti. It is obtained by subtracting Darwin's sea-level pressure from Tahiti's (Tahiti minus Darwin). Researchers derived this index after noting a strong, but negative correlation between the sea-level pressure values at the two locations (see Figure 2-27). They found that if the pressure was high at Darwin, it was correspondingly low at Tahiti, and visa-versa. A high SOI (positive) value means sea-level pressure is lower over the western Pacific and the Indian Oceans than the eastern Pacific. A low SOI (negative) value means the opposite.

El Niño. The El Niño phase averages 18 months. It begins with elevated sea-surface temperatures in the eastern Pacific, usually in December (hence the term "El Niño," which means "Christ Child"). These temperature anomalies gradually diminish as they propagate westward, however, and temperatures in the western Pacific Ocean are 3-5 Fahrenheit (2-3 Celsius) degrees lower than normal. These lower temperatures are linked to changes in the monsoon over India. Other atmospheric changes associated with the southern oscillation are not fully understood, but El Niño appears to be connected to variations in sea-surface temperatures in the Atlantic Ocean.

The El Niño begins to appear in the western Pacific during March and April. It reaches peak intensity during the southwest monsoon and lasts into the northeast monsoon. Radical changes to the monsoon system occur during an El Niño year. The North Pacific high strengthens and shifts unusually far south during the southwest monsoon. The high covers a larger area and extends further west. Over the Indian Ocean, the Walker circulation (zonal winds) weakens while the Hadley circulation (meridional winds) strengthens. This results in a weakening or reversal of the easterly wind flow over the Indian Ocean and prevents the movement of tropical disturbances into the Bay of Bengal from the

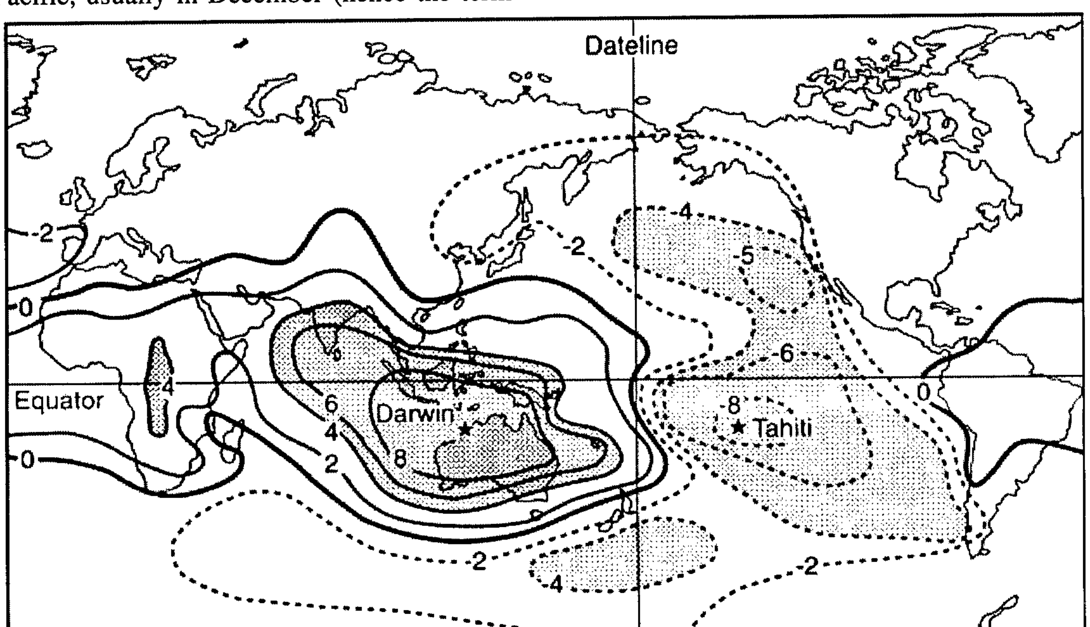


Figure 2-27. Southern Oscillation Pressure. The island of Tahiti and Darwin, Australia are considered to be at the opposite ends of the Walker circulation. As a result, the sea-level pressure difference between them is used to measure the southern oscillation. The numbers represent a statistical measure called the correlation coefficient. They show the pressure variation at Tahiti is inversely related to the variataion at Darwin as are locations near to Darwin. (Adapted from Hastenrath, 1991 and Trenberth, 1984)

western Pacific. In normal years, these tropical disturbances generate much of the rain that falls on eastern India and Bangladesh during the southwest monsoon. Also, the ET is usually weaker than normal during an El Niño cycle. It lies south of its normal position, especially during the early stages.

South Asia can expect a drop in precipitation during an El Niño, especially during the southwest monsoon. An analysis of 22 strong and moderate El Niño events between 1871 and 1978 indicated below normal rainfall occurrences during the southwest monsoon during 17 of those events (see Table 2-1). Of the 17 years of below normal rainfall, eight showed a drought occurred. A drought over India is said to occur when the all-India southwest monsoon rainfall is more than 12.5 percent below normal. A strong El Niño event occurs when the positive sea-surface temperature anomalies off the coast of Peru exceed 5 Fahrenheit (3 Celsius) degrees. For a moderate event, the anomalies exceed 3 Fahrenheit (2 Celsius) degrees.

Table 2-1. Summary of El Niño Years and All-India Southwest Monsoon Rainfall. Normal rainfall is 33.61 inches with standard deviation of 3.27 inches (S = strong and M = medium). (Mooley and Parthasaranthy, 1983)

		All-India Summer Monsoon Rainfall		
	El Niño		% Departure	
Year	Intensity	Amount (in)	from Normal	Category
1871	M	33.32	-0.9	Below Normal
1877	S	23.79	-29.2	Drought
1880	M	32.18	-4.3	Below Normal
1884	S	36.61	8.9	Excess
1887	M	35.32	5.1	Above Normal
1891	S	31.09	-7.5	Below Normal
1896	M	32.47	-3.4	Below Normal
1899	S	24.75	-26.4	Drought
1902	M	31.17	-7.3	Below Normal
1905	M	28.17	-16.2	Drought
1911	S	28.88	-14.1	Drought
1914	M	35.42	5.4	Above Normal
1918	S	25.54	-24.0	Drought
1925	S	31.63	-5.9	Below Normal
1929	M	32.28	-4.0	Below Normal
1939	M	31.07	-7.6	Below Normal
1941	S	28.72	-14.6	Drought
1953	M	36.24	7.8	Above Normal
1957	S	30.90	-8.1	Below Normal
1965	M	27.85	-17.2	Drought
1972	S	25.74	-23.4	Drought
1976	M	33.68	0.2	Above Normal

As the transition towards the northeast monsoon begins, rainfall over some areas of the region returns to normal. In some years, rainfall is above normal. Studies indicate Sri Lanka and extreme southern India have normal or above normal rain during the post-monsoon season (October-December) of an El Niño year. During the post-monsoon season of an El Niño year, researchers note tropical cyclones tend to move along a more west-to-southwest track towards southern India and Sri Lanka. Normal movement is towards the west and northwest.

La Niña. When a La Niña is underway, conditions over South Asia tend to be the opposite of those during an El Niño. The Walker circulation strengthens and the Hadley circulation weakens. The equatorial trough is stronger and more active than normal. Above normal rainfall can be expected during the southwest monsoon. Some areas can expect excessive rain that leads to flooding. Historically, almost all of the significant flooding events over the Indian subcontinent occurred during a La Niña. Rainfall patterns during the post-monsoon season (October-December) of a La Niña are also opposite those of an El Niño. This is particularly true for Sri Lanka and the southeastern portion of India where below normal precipitation can be expected. This results from the ET remaining north of Sri Lanka for most of the post-monsoonal season.

Synoptic Features

Non-Tropical Features

Fronts. Fronts transit northern India during the northeast monsoon when lows move in from the northwest. A warm front may be seen ahead of the low while a weak cold front trails. Thunderstorms may accompany the cold front. Well-defined highs rarely follow these lows.

Western Disturbances. These are northeast monsoon migratory lows that move east across northern India. They occur between November and May but

are most frequent in December through April. Some originate in the North Atlantic Ocean and Europe, make their way eastward, usually via the Mediterranean Sea, then move into the region from the Caspian Sea. After moving into India, these systems travel eastward along the southern periphery of the Himalayas. Some may reach far northeastern India. The low tracks generally remain north of 20° N (see Figure 2-28). Sometimes, a weak low develops in a lee-side trough along the eastern slopes of the Sulaiman Range of central Pakistan. This low tends to move east-northeastward into India. From there, it moves east along the same routes taken by other migratory lows. About 4 to 7 disturbances per month move across northern India between December and April. In November and May, the number of disturbances drop to 2 per month. Precipitation from these lows is usually rain over the lowlands and snow over the mountains.

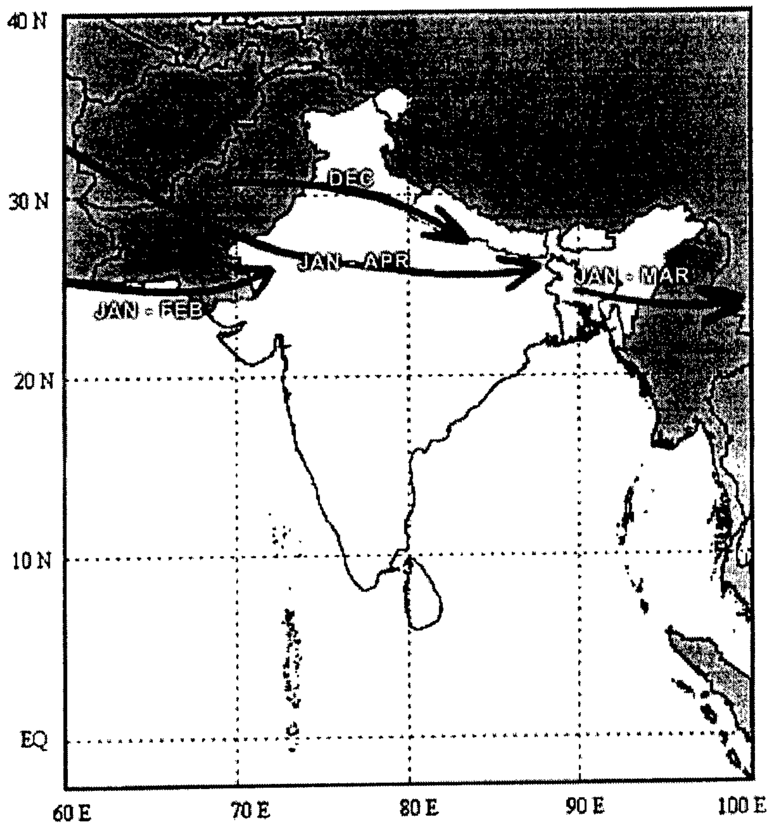


Figure 2-28. Principal Tracks of "Western Disturbances." These systems travel eastward along the southern periphery of the Himalayas. (Adapted from Pant and Kumar, 1997)

Coastal Trough. A weak pressure trough often develops off the southwest coast of India during the southwest monsoon. It forms near 13°-15° N and shifts north, though it may appear and disappear in place anywhere along the coast. This trough strengthens the southwest monsoon rainfall in the adjacent coastal region.

Tropical Features.

Tropical Waves. Also known as easterly waves, tropical waves are periodic, west-moving disturbances in the easterly winds. They are most identifiable at low levels as weak pressure troughs with wind shifts. Convergent air occurs toward the rear of the waves and often triggers showers and thunderstorms. The waves travel a mean of 400 miles (640 km) per day. Mid-level winds are lighter than at the surface. Waves are more active when close to the ET.

Tropical Vortices. A vortex is a generic term given to cyclonic cloud and circulation patterns. Quite common in the tropics, some develop into tropical cyclones, but many more dissipate without reaching tropical cyclone intensity. Tropical vortices can be schematically arranged in terms of vertical motion (Figure 2-29). In the fine weather vortices (anticyclones, heat lows, and upper-tropospheric cyclones/cold lows), there is subsidence at the middle-tropospheric levels. For the bad weather vortices (tropical cyclones, monsoon depressions, and mid-tropospheric cyclones), middle-tropospheric air rises.

Monsoon Depressions. These lows play a significant role in the southwest monsoon. They account for much of the rain over India and enhance the monsoonal flow. A monsoon depression is a low that develops over the northern Bay of Bengal north of 17° N during the southwest monsoon (see Figure 2-30). One sometimes develops over the Arabian Sea, but they are more common over the Bay of Bengal. In either region, formation usually takes place near or equatorward of the ET in a strongly baroclinic environment with marked easterly shear.

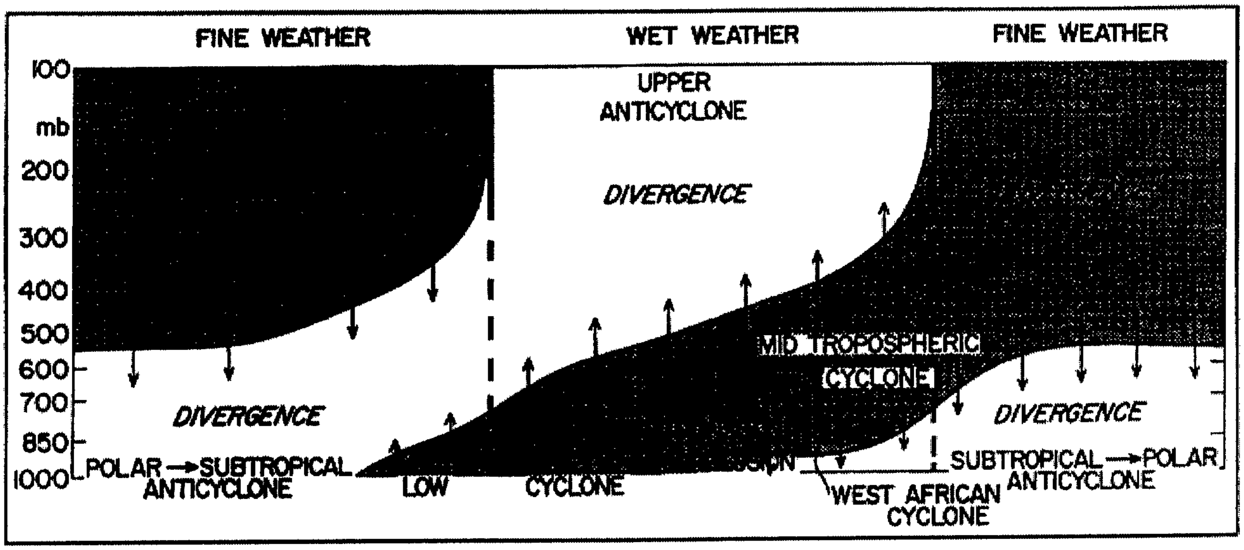


Figure 2-29. Circulation Components of the Atmosphere. Arranged according to weather, divergence, and vertical motion. Solid lines denote levels of non-divergence. (Ramage, 1995)

Origin. The India-Myanmar trough is over the Bay of Bengal during the southwest monsoon. This trough bends southward with increasing height. Tropical waves and disturbances move into the Bay of Bengal from the east. Some disturbances are remnants of western Pacific tropical cyclones. When the tropical wave or disturbance reaches the northern Bay of Bengal, the India-Myanmar trough intensifies. When this happens, a closed low often develops. The trough sometimes intensifies and develops a closed low without a tropical wave or disturbance. This happens less than 15 percent of the time. Within about a day, the low develops into a depression with sustained winds of 22-33 knots. Sometimes the depression develops into a tropical cyclone (sustained wind speeds 64 knots or greater), but this is not likely due to the strong vertical wind shear of the southwest monsoon and its close proximity to the coastline. Intensification to tropical cyclone strength is most likely to occur in September when the vertical wind shear eases as the onset of the transition to the northeast monsoon begins to set up.

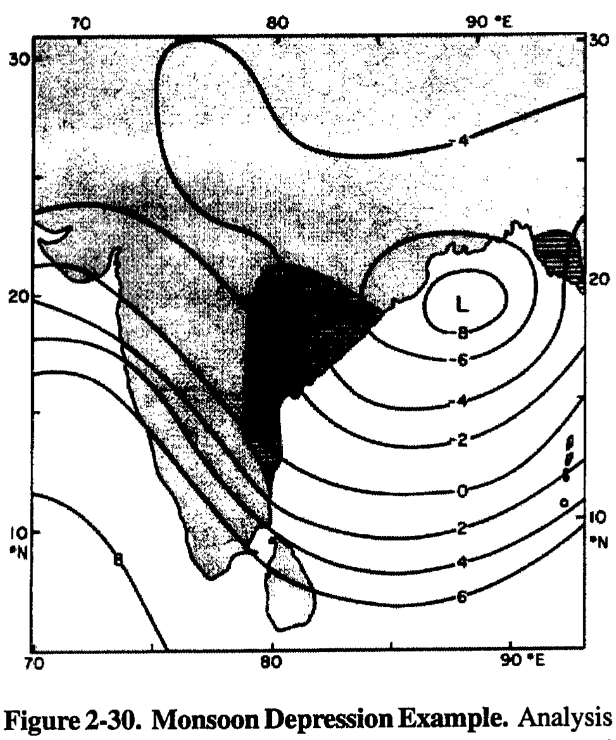


Figure 2-30. Monsoon Depression Example. Analysis of the 1000-mb pressure field over the Bay of Bengal for 1200Z on August 20, 1967. The contours are in decameters. The hatched areas are regions of continuous rain. (Pant and Kumar, 1997 from Hamilton, 1987)

Structure. A monsoon depression is a tropical system, but not a tropical cyclone. It has a cold core near the surface and a warm core in the upper levels (about 500-300 mb). A tropical cyclone, on the other hand, is warm core throughout its entire vertical structure. The monsoon depression's circulation, which can have a diameter of 300-625 miles (500-1,000 km), is strongest at 3,000-5,000 feet. The circulation begins to weaken above 5,000 feet and generally disappears above 300

mb. At the surface, the central pressure is 3-10 millibars below that of the surrounding environment. The center is generally cloud-free. Upward vertical motion is concentrated just south of the surface center (see Figure 2-31). Winds are strongest to the south of the center because of the enhancement of the wind field by the moderate to strong westerlies south of the depression. On satellite imagery, the monsoon depression may resemble a tropical cyclone depression in a stage well before an eye forms.

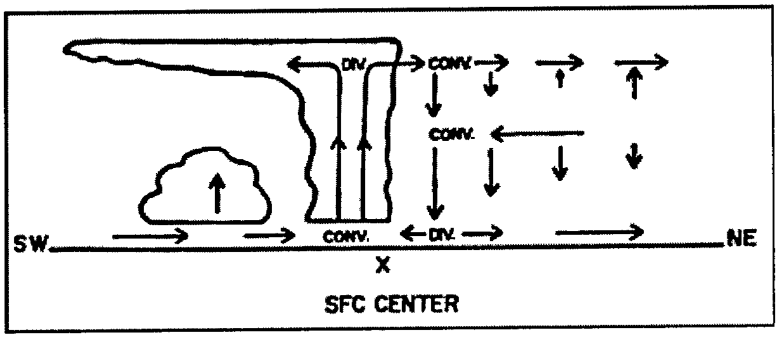


Figure 2-31. Schematic Drawing of the Vertical Circulation across a Monsoon Depression. The asymmetrical cloud field around a depression is attrubuted to the large horizontal wind shear in the vertical. (Ramage, 1995 from Douglas, 1987)

Frequency and Duration. The number of monsoon depressions that develop over the Bay of Bengal varies from year to year, but around 2 per month can be expected between June and September. They occur more frequently in the latter part of the southwest monsoon (see Figure 2-32). The average life span is 4-6 days; some last as long as 10 days.

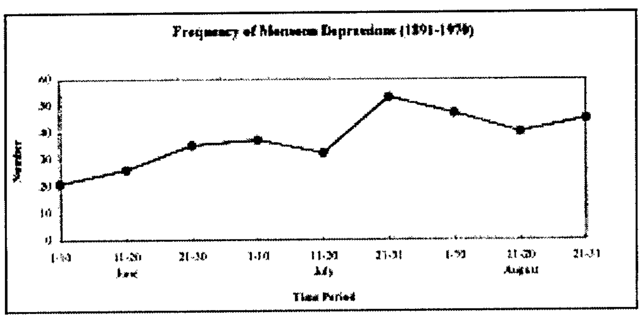


Figure 2-32. Temporal Distribution of the Number of Monsoon Depressions in the Bay of Bengal during June - August. (Adapted from Rao, 1976)

Movement. Once a monsoon depression forms, it moves west-northwest with the upper air flow along one of two tracks (see Figure 2-33). Track A is followed by the depressions once the southwest monsoon establishes itself over northern India. After moving onshore and across central India, the monsoon depression generally weakens in intensity as it is cut off from its moisture supply. It then moves towards the west-northwest and merges with the Asiatic low. Occasionally, the depression gains a fresh moisture supply from the Arabian Sea. The depression reintensifies and takes a more westwardly track. It eventually reaches Gujarat in western India and dumps heavy rain over that region. A mid-latitude westerly trough will sometimes induce a west-moving depression to recurve to north, then north-northeast. This depression moves into the Himalayan mountains and dissipates with very heavy rainfall over the mountain slopes. It is also possible for north-moving depressions to shift the ET northward where it settles against the mountains. This causes a monsoon break.

Rainfall. Widespread heavy rainfall is common with monsoon depressions. The amount of rainfall depends on a number of factors:

- Intensity of the depression.
- Vertical velocity in the different sectors of the depression's circulation.
- Moisture content of the air around the depression, which has to be continuously renewed and replenished.
- Topography.
- The state of the depression. Is it developing or dissipating?
- Whether or not the system is recurving.

For monsoon depressions that move towards the west or northwest, most of the rain falls over the southern and southwestern sectors of the low. The heaviest rainfall generally occurs in the southwestern sector away from the center. The wind field around the monsoon

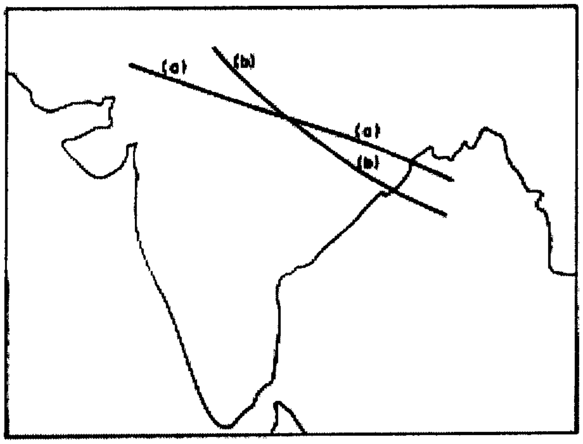


Figure 2-33. Monsoon Depression Tracks. Track A is followed by the depressions once the southwest monsoon establishes itself over northern India. Track B is followed during early June when the monsoon is getting established and during late September, when the southwest monsoon begins its withdrawal. (Asnani, 1993)

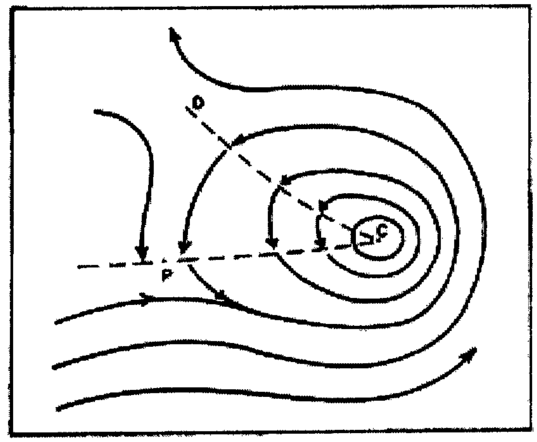


Figure 2-34. Wind Field of a Monsoon Depression. Two lines of discontinuity are seen in the wind directions, one extends westwards (line CP), the other extends northwestward (line CD). The northerly and westerly air currents around the depression meet near point P. (Asnani, 1993)

depression is asymmetrical (see Figure 2-34). This results in a strong horizontal velocity convergence zone south of the line CP. This convergence zone causes the heaviest rainfall to occur in the southwestern sector of the depression.

If a monsoon depression recurves to the north or northeast in advance of a mid-latitude trough, the zone of maximum rainfall will shift to the northern sectors after recurvature. A strong, horizontal velocity convergence zone is created along the leading edge of the mid-latitude trough between the monsoon depression's center and the Himalayas. The heaviest rains fall on the slopes of the Himalayas in advance of the depression.

Researchers have been studying the monsoon depression and have drawn conclusions on their rainfall patterns:

- The immediate vicinity of the depression's center and the outer periphery of the circulation field area are generally free of heavy rainfall.

- For westward-moving depressions, the heaviest rainfall occurs in the southwest quadrant, about 125-250 miles (200-400 km) from the center. A secondary zone of maximum rainfall lies about 500 miles (800 km) west of the center.

- Rainfall amounts of 12 inches (305 mm) or greater in a 24-hour period occur quite often in monsoon depressions and cause serious flooding.

- Heavy rainfall in the rear sector of a monsoon depression occurs in only exceptional cases.

- When a monsoon depression moves west of 80° E, the rainfall amounts increase considerably. This may be, at times, 200 percent of that normally received. This is due to the depression being reintensified by the Arabian Sea branch of the southwest monsoon.

Effects on the Indian west coast. When a monsoon depression forms in the northern Bay of Bengal, India's west coast tends to see an increase in rainfall. In 70 percent of the monsoon depressions studied between 1956 and 1975 (111 cases), a monsoon depression in the Bay of Bengal leads to a strengthening of the southwest monsoon flow in the Arabian Sea. This results in a rainfall increase along the west coast only if an active coastal trough develops or exists along India's west coast. This trough allows cyclonic circulation (mid-tropospheric cyclone) to develop over the northeastern Arabian Sea and the adjacent land areas between 850 and 700 mb. The Somali jet and the low-level winds strengthen, and when coupled with the cyclonic vorticity,

result in increased rain. The rainfall increase also occurs along the Western Ghats. No appreciable increase in rainfall is noted along the coastline on the southwestern tip of India.

Mid-Tropospheric Cyclones. These systems develop during the southwest monsoon between the 700 and 500 mb. The northeast Arabian Sea near the equatorial trough is the favored location for development in the Indian Ocean. The mid-tropospheric cyclone is hardly detectable near the sea-level or at the 200-mb level, yet it is the major producer of rain along India's western coast. Some characteristics are listed below:

- Essentially stationary; movement, if any, is westward.
- Life cycle about 10 days.
- Maximum wind speed of 40 knots near 600 mb.
- Pronounced warm core above 600 mb; slight cold core below.
- Total rainfall amounts of 7.9 inches (201 mm) per 24 hours are not uncommon.

Figure 2-35 depicts the kinematic analyses of the near-surface and 600 mb of an Arabian Sea mid-tropospheric cyclone observed in 1963. A weak coastal trough is the only sign of a surface disturbance while a well-developed cyclone exists at 600 mb. Figure 2-36 shows the vertical motion and cloud distribution associated with the mid-tropospheric cyclone, and Figure 2-37 shows its horizontal cloudiness and rainfall distribution.

Tropical Cyclones. These synoptic-scale storms pose a serious threat to the north Indian Ocean, especially the Bay of Bengal. When it comes to storm surges, the Bay of Bengal is the most dangerous tropical cyclone basin in the world. Not only are its physical characteristics conducive to very large storm surges, its low-lying coastal regions are heavily populated.

Tropical cyclones develop over tropical waters and have well-organized circulations. They usually develop from pre-existing disturbances and intensify into the following categories:

- Tropical Depressions. These are the weakest tropical cyclones with sustained wind speeds near the center less than 34 knots. Minimal wind damage occurs, but heavy rainfall can cause flooding.

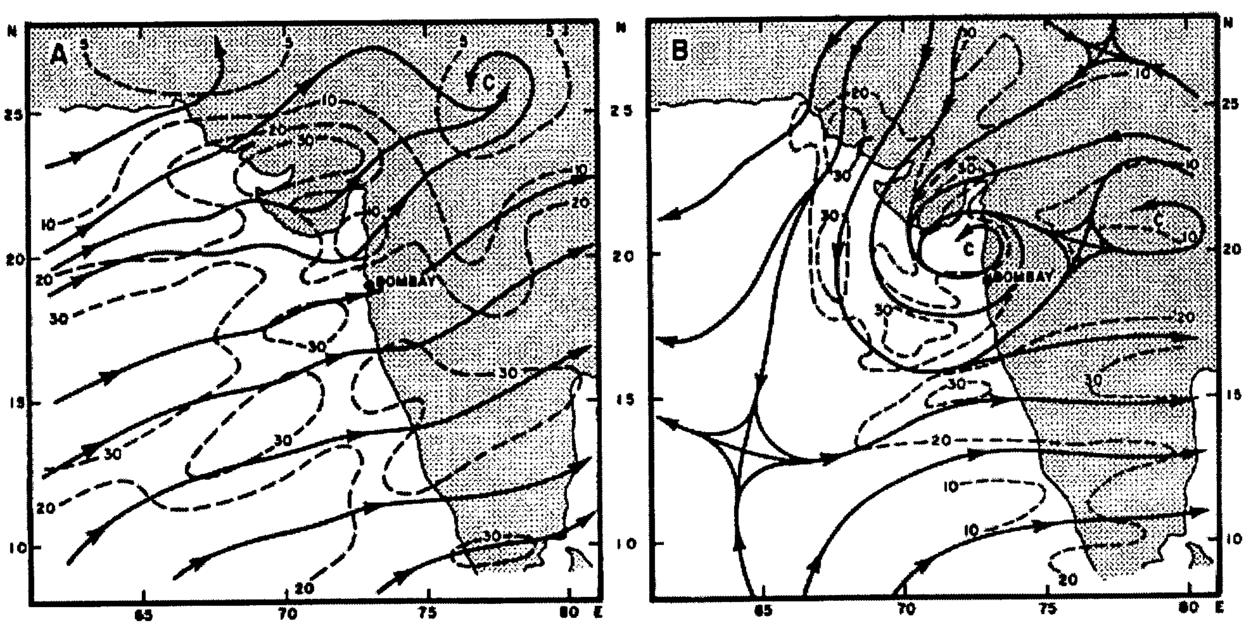


Figure 2-35. Arabian Sea Composite Kinematic Analyses (knots) for 1-10 July 1963. (A) depicts the near surface layer (1600 to 3000 feet/500 to 900 meters); (B) is the 600-mb level, showing a well-developed mid-tropospheric cyclone over western India. (Ramage, 1995 adapted from Miller and Keshavamurthy, 1968)

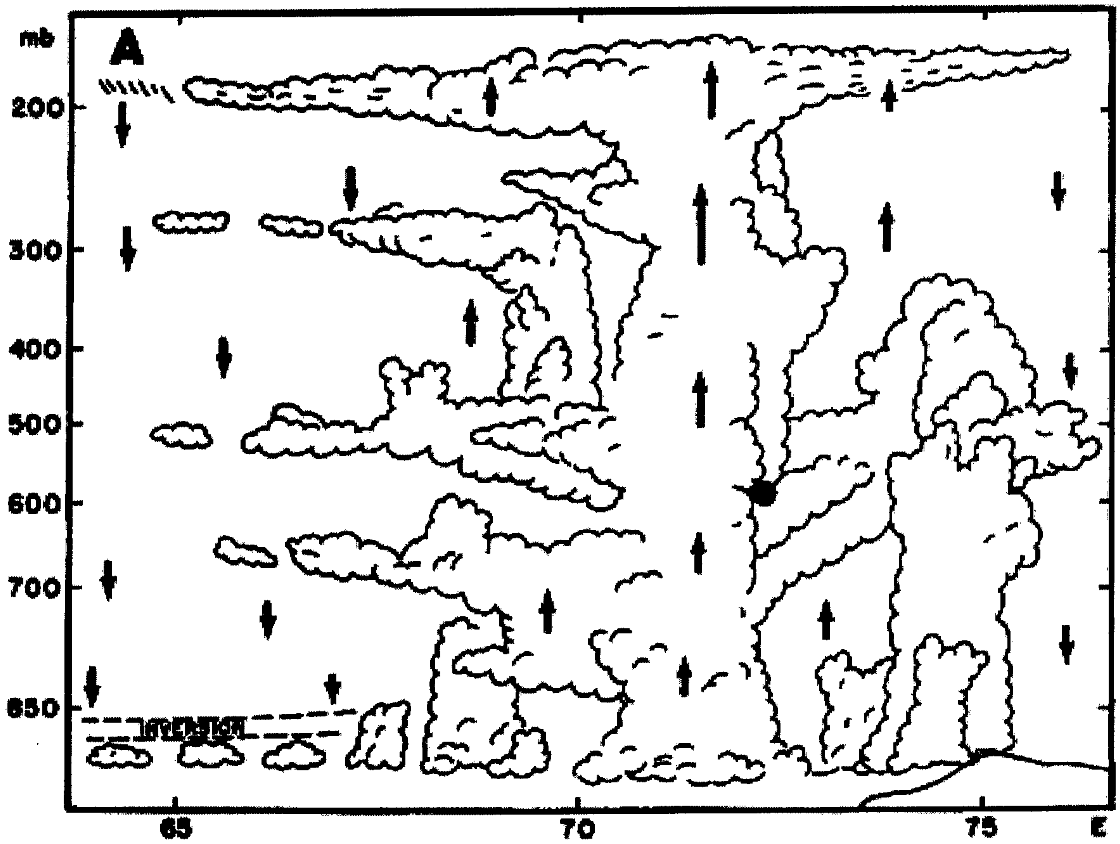


Figure 2-36. Mid-Tropospheric Cyclone Cross-Section. Vertical east-west cross-section of the mid-tropospheric cyclone shown in Figure 2-35. Large dot locates the center at 600 mb. Arrows depict relative vertical motion computed from composite kinematic analyses. (Ramage, 1995 adapted from Miller and Keshavamurthy, 1968)

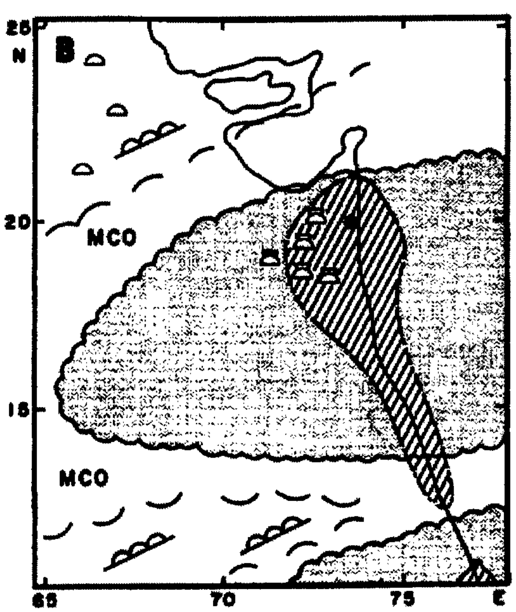


Figure 2-37. Mid-Tropospheric Cyclone Cloud and Rainfall Fields. Horizontal cloudiness and rainfall distribution of the mid-tropospheric cyclone depicted in Figure 2-35. The hatched area delineates rainfall of more than 1.6 inches (41 mm) per day. Shaded areas show broken-to-overcast middle or high cloud coverage. (Ramage, 1995 adapted from Miller and Keshavamurthy, 1968)

- Tropical Storms. These are tropical cyclones with sustained wind speeds of 34-63 knots near the center. Significant wind damage to poorly designed or constructed structures and major flooding occurs.

- Typhoons. Typhoons, the most powerful tropical cyclones, are known for their destructive high winds, heavy rains, and impressive storm tides. Sustained winds of at least 64 knots are near the center; some typhoons sustain wind speeds over 150 knots. Typhoons with sustained wind speeds of at least 130 knots are called "super typhoons." Extensive to catastrophic wind damage is likely with these storms when landfall occurs. Extensive flooding is likely with heavy rain and high storm tides.

Origin. Tropical cyclones develop in maritime air over the open waters, usually on the equator side of the subtropical ridge axis. Some tropical cyclones in the Bay of Bengal originate in the western Pacific Ocean and the South China Sea. Others form when the remnants of western Pacific typhoons cross Indo-China and regenerate over the Bay of Bengal. Development is most favorable in the vicinity of the ET. Other favorable meteorological conditions are:

- A convectively unstable air mass.

- A sea surface temperature of 81°F (27°C) or greater.

- The presence of positive vorticity.

- A tropical wave in or moving into the area.

- Low-level convergence and upper-level divergence in the area of the disturbance.

- Weak vertical wind shear in the zonal horizontal wind flow.

- Development must occur at least 3 degrees latitude from the equator.

Structure. A tropical cyclone is warm core. The most obvious feature of a mature tropical cyclone is the eye, as seen in Figure 2-38. The eye is normally 6-12 miles (10-20 km) across and coincides with the wall cloud, the location of the most vigorous convection, and heaviest rain in the storm. Inside the eye, skies are generally clear with relatively light winds. The strongest winds of a tropical cyclone are around the center and near the surface and decrease outward. There is cyclonic circulation in the lower levels and anticyclonic circulation aloft. This allows the tropical cyclone to maintain itself through air inflow in the lower levels and outflow at the top. Cut off either and the system will die.

Frequency and Duration. The north Indian Ocean is fairly active, nearly 5 tropical cyclones per year, and most occur over the Bay of Bengal (see Figure 2-39). Figure 2-40 contains a month by month breakdown of tropical cyclone occurrence. Table 2-2 shows the mean monthly occurrence. The data shows a clear seasonal pattern. Tropical cyclones are most likely to develop

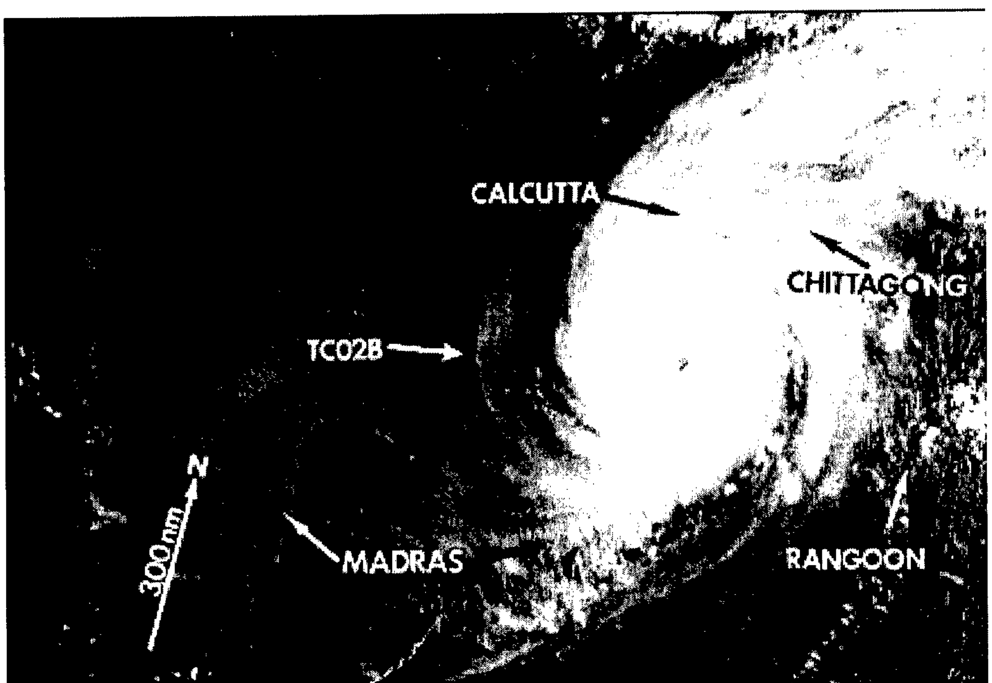


Figure 2-38. Tropical Cyclone 02B in Bay of Bengal. Image of tropical cyclone bearing down on the coast of Bangladesh. Estimated winds were 130 knots. (Courtesy Joint Typhoon Warning Center, 1991)

during the two transition seasons between the monsoons.

The late year transition (post-monsoon season) has the annual maximum activity. The equatorial trough lies essentially east-west over the north Indian Ocean from mid-September to mid-December. Its intra-season position varies from near 20° N in late September to around 5° N by early December. As the ET moves south, easterly flow reestablishes itself in the northern portions of the Bay of Bengal and the Arabian Sea while a westerly wind flow exists equatorward of the ET. This creates the ideal low-level circulation pattern for tropical cyclone development. The hot season is the second most active period of tropical cyclone activity. It is shorter than the post-monsoon active period, and its circulation changes are more rapid. As a result, the favorable period for tropical cyclone period is shorter, essentially from mid-April to mid-June.

The mean circulation during the southwest monsoon is not favorable for tropical cyclone development. The ET lies over land, and westerlies cover the north Indian Ocean. The strong, upper-level easterlies over the northern Bay of Bengal create strong vertical shear detrimental to tropical cyclone development. Occasionally, the ET moves south over the northern Bay of Bengal. When this happens, a monsoon depression develops and moves northwest along the ET. Most monsoon depressions do not attain tropical cyclone status before making landfall.

During mid-December to mid-April, the ET lies in the south Indian Ocean or very close to the equator. Both positions are unfavorable for tropical development. The

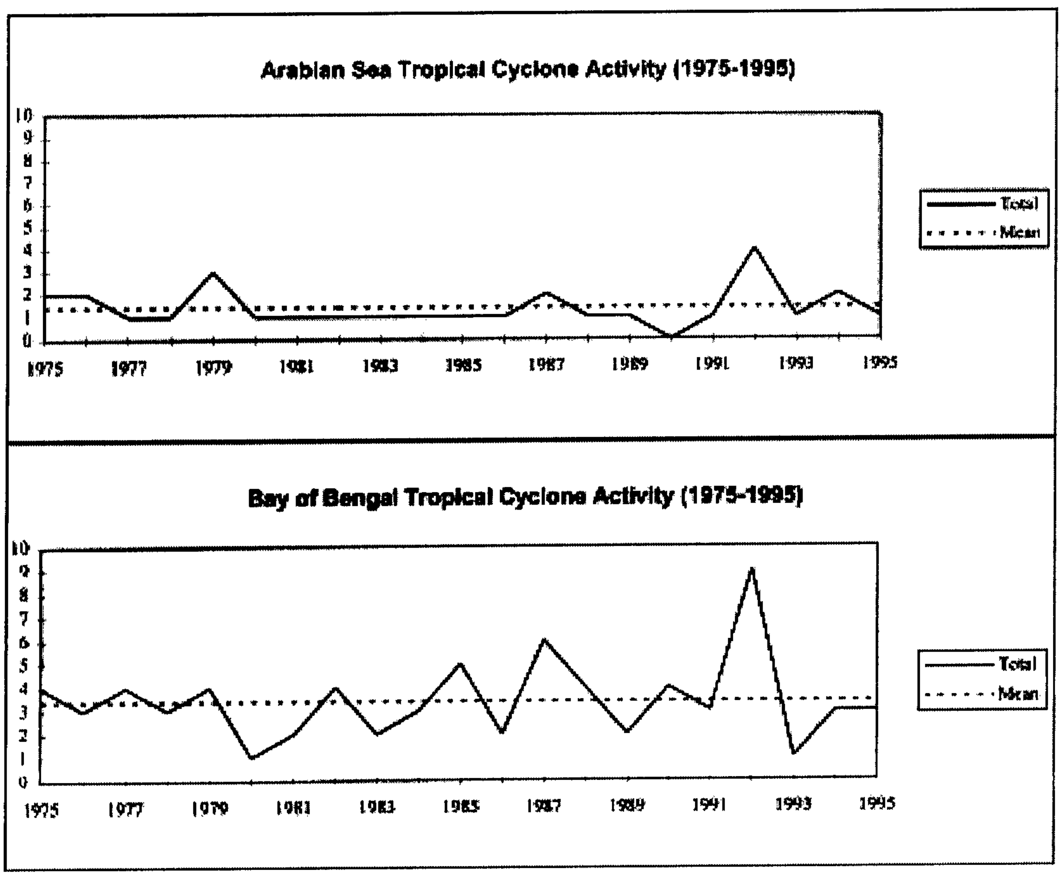


Figure 2-39. North Indian Ocean Tropical Cyclone Activity. Shows yearly total of tropical cyclones over a 21-year period (1975-1995) for the Arabian Sea and the Bay of Bengal. Comparison is made to the mean annual number for the same time period and compares it to mean number over the period. (Adapted from *1995 Annual Tropical Cyclone Report*)

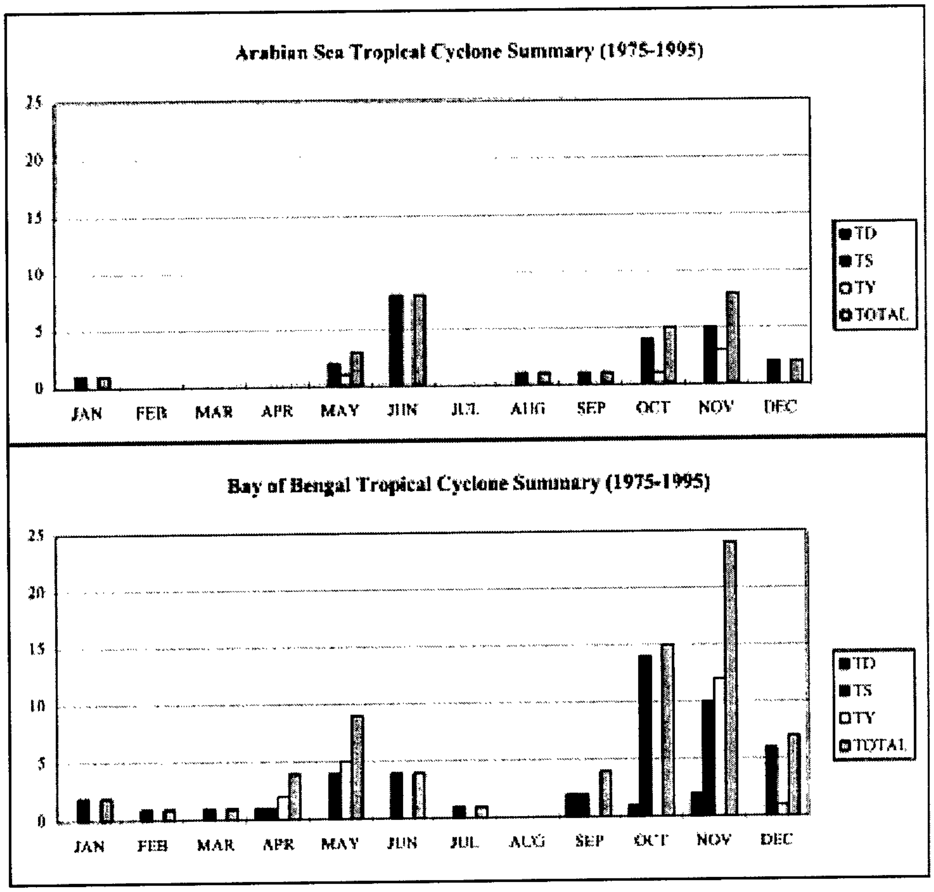


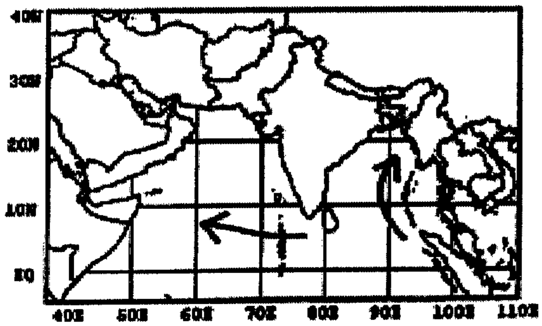
Figure 2-40. Tropical Cyclone Occurrence in the North Indian Ocean. Shows the monthly breakout on the number of tropical cyclones that occurred between 1975 and 1995 in the Arabian Sea and the Bay of Bengal. TD = Tropical Depression (winds <35knots); TS = Tropical Storm strength cyclones (winds 35 - 63 knots); and TY = Typhoon strength cyclones (winds ≥64 knots). (Adapted from *1995 Annual Tropical Cyclone Report*)

Table 2-2. Mean Tropical Cyclone Occurrence, by Month, for the North Indian Ocean. Period of Record: 1975-1995. Asterisk (*) denotes at least one tropical cyclone occurred. (Adapted from *1995 Annual Tropical Cyclone Report*)

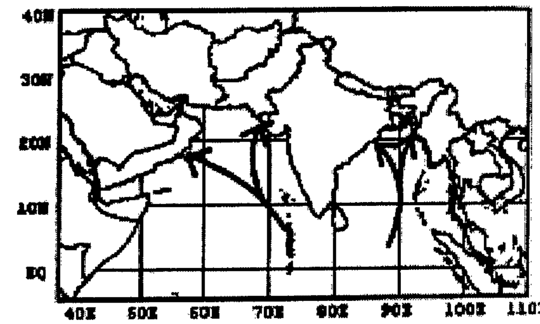
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr
Arabian Sea	*	0	0	0	0.1	0.4	0	*	*	0.2	0.4	0.1	1.4
Bay of Bengal	0.1	*	*	0.2	0.4	0.2	*	0	0.2	0.7	1.1	0.3	3.4
Total:	0.1	*	*	0.2	0.5	0.6	*	*	0.2	0.9	1.5	0.4	4.8

cross-equatorial flow sometimes increases and pushes the ET north to between 5° and 10° N, which makes tropical cyclone development possible. Development doesn't exceed a weak tropical storm.

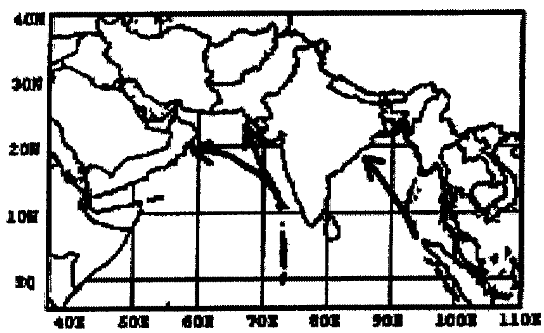
Movement. The tropical cyclone tracks in Figure 2-41 are mean tracks for the given period and are drawn along axes of maximum cyclone frequency. These mean tracks hide the variability of the individual tropical cyclone tracks (Figure 2-42). The environment of a tropical cyclone largely controls its movement. The biggest factor is the position and intensity of the subtropical ridge. Movement in the north Indian Ocean is generally east to west or west-northwest. North movement is possible if there is a weakness in the ridge.



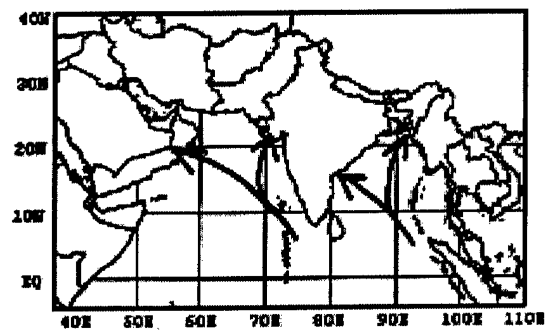
January 1 to April 30



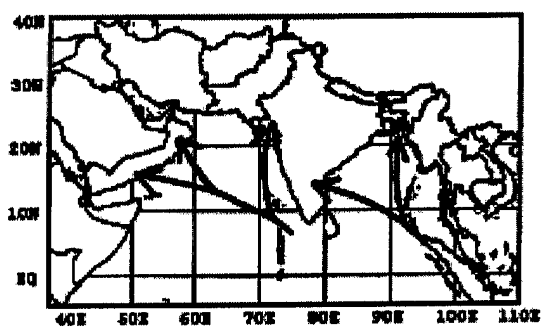
May 1 to July 31



August 1 to September 30



October 1 to November 30



December 1 to December 31

Figure 2-41. Tropical Cyclone Tracks for the North Indian Ocean. The mean tracks (in the five charts) are drawn along the area of maxium tropical cyclone frequency. (Adapted from Pant and Kumar, 1997)

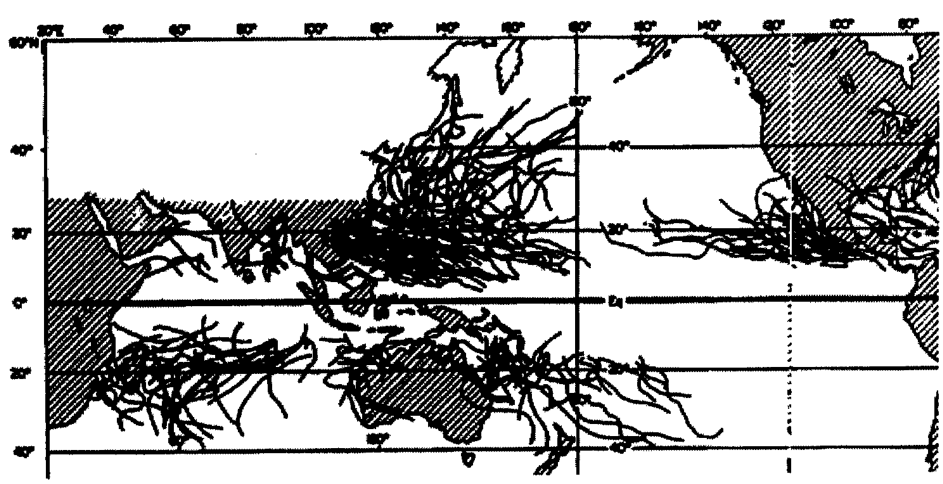


Figure 2-42. Tropical Cyclone Tracks for a 3-Year Period. The figure shows the variability of tropical cyclone tracks. (Ramage, 1995 adapted from Gray, 1978)

Cloud Features

Cloud Clusters. Cloud clusters, the primary cloud feature of the equatorial trough, have extensive stratiform decks with rainfall concentrated in embedded convection (Figure 2-43) capped by cirrus shields. They are formed and maintained by steady, low-tropospheric convergence. Cloud clusters last 1-3 days and extend 185-620 miles in diameter. They undergo diurnal intensity fluctuations as they move with the low-level tropospheric wind flow. A few eventually evolve into tropical cyclones. There are two types of cloud clusters, squall and non-squall. A squall cluster occurs with a tropical squall line. It undergoes explosive growth and moves rapidly after forming. On satellite imagery, this cluster has a distinctive convex leading edge. The non-squall cluster occurs most often. It is slow moving and lacks the distinctive oval cirrus shield and arc-shaped leading edge.

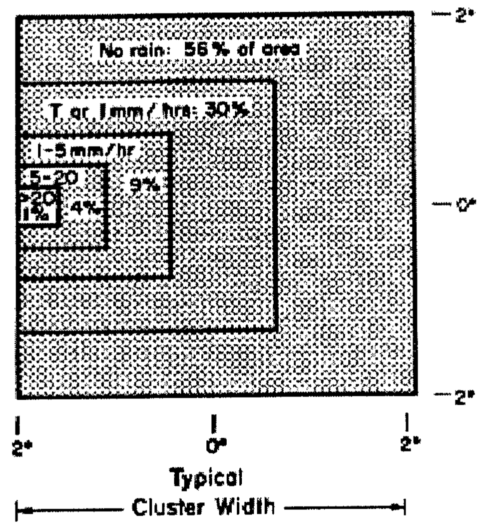


Figure 2-43. Area Distribution of Rainfall Intensity within a Typical Cloud Cluster. Shows the percentage of the horizontal cluster area occupied by various rainfall intensities. It does not mean all rainfall is concentrated in a small quadrant at the leading edge of the cluster. (Higdon, et al, 1997 from Ruprecht and Gray, 1976)

Mesoscale Convective Complexes (MCCs). The tropical MCCs that affect South Asia are most frequent over India and Bangladesh. MCCs develop with the onset and withdrawal of the southwest monsoon. During April to June, most MCCs develop over eastern India and Bangladesh. There is little or no MCC activity over the northwest. MCC activity spreads northwestward as the summer progresses. It occurs over most of the region by late August. MCC development is greatest during July to September. After development, MCCs produce heavy rain and hail. About 40 percent of the rain from tropical MCCs comes from stratiform clouds. Hail formation in tropical MCCs is by riming. It is softer than the hail in MCCs outside the tropics. Although MCCs occur throughout the region, they tend to form mostly over land (see Figure 2-44). The trigger

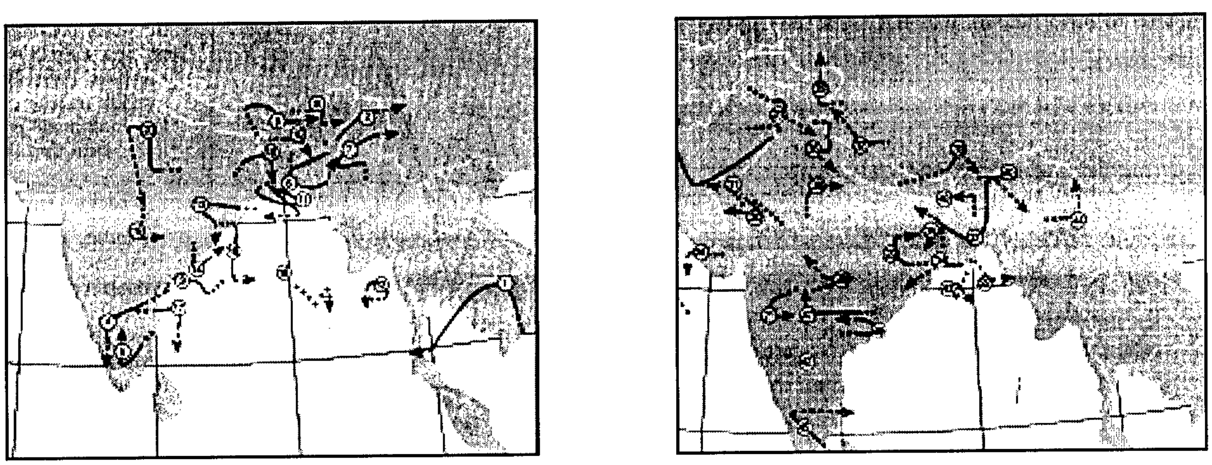


Figure 2-44. Mesoscale Convective Complexes over South Asia during 1988. Shows the tracks of MCCs from (a) April to June and (b) July to September. Dots indicate the pregenesis stage; solid lines MCC paths between genesis and dissipation; dashes indicate the dissipating or remnant stage. The circled numbers correspond to the MCC case number and the MCC centroid position at maximum areal extent. The plus (+) signs indicate where an MCC transformed into a tropical or monsoon depression. (Laing and Fritsch, 1993)

for many is the interaction of convective cells or cloud clusters with a land breeze or a sea breeze front. Others are orographically induced. Some are formed by the interaction of the convective cells with the ET. In those MCCs that form over the open water, convergence of the low-level wind flow is usually the trigger. MCC movement appears to be with the mean 700-500 mb wind flow. Some, especially those that form over the open water, can intensify into tropical or monsoon depressions. Others sometimes grow until they have dimensions similar to a tropical cyclone. MCCs are predominately nocturnal and have an average life span of 12 hours. Thunderstorms develop first around 1700L. MCC formation usually follows around 2200L, and dissipation occurs between 0700L and 1400L. They usually reach maximum intensity between 0000L and 0600L. Some MCCs, especially those that form over water away from land masses, can last 2-3 days under the right conditions. They still, undergo a diurnal fluctuation in convection.

Mesoscale Weather Events

Nor'westers. These are lines of severe thunderstorms that frequent northeast India, particularly the lower Ganges River basin (West Bengal) and Bangladesh, in late winter and all of the hot season. They occur as from February to the middle of June. Development takes place when warm, moist, conditionally unstable air that flows up from the Bay of Bengal clashes with cool, dry air that flows down from the Himalayas. The southwest monsoon puts an end to nor'westers as the southerly air flow dominates the subcontinent and prevents the flow of cool air from the north.

Nor'westers generally move from the northwest to southeast. They less commonly move from the north or northeast. Late afternoon or evening on a warm, humid day is the favorite time for development. The storms rarely last more than 3-4 hours and are followed by clear, cool weather. Nor'westers often occur in the same place and around the same time 3 or 4 days in a row. Strong gusty winds, torrential rains, hail and severe lightning accompany these storms. Winds in excess of 85 knots are possible. Nor'westers also spawn tornadoes. As the season progresses, nor'wester activity extends northward and westward, the height of the tops of the thunderstorms increases, and the storms become more severe. but the occurrence of hail decreases. As the pre-monsoon season progresses:

- The ET moves into the Gangetic Plain and intensifies.

- Nor'wester activity spreads to the north and west as the horizontal extent and vertical depth of the maritime air increases northward and westward.

- The cloud condensation level (CCL) lowers during the period. The buoyant energy also increases to allow for greater penetration of the convective clouds into the lower stratosphere.

- As the Tibetan high sets up, wind speeds in the middle and upper troposphere decrease. This reduces vertical wind shear over the region and removes the barriers to thunderstorm development.

Hailstorms. The mean rate of hailstorms over the subcontinental plains is 1 per year or two. The foothills of the Himalayas have the greatest occurrence, but coastal areas south of 20° N and the Gujurat coast are practically hail-free. The plains north of 20° N experience a hailstorm about once every 1-2 years, except for Gujurat and the desert areas where the frequency is lower. The hot season is the period of greatest hail activity. Hail events also occur during the northeast monsoon (dry) season, but to a lesser extent. Hailstorms occur most of the year along the foothills of the Himalayas. The chance for hail diminishes greatly once the southwest monsoon arrives.

Tornadoes. These violent events are called "Hat-ishnura" (elephant's trunk) in northeast India where a majority of them occur over the Indian subcontinent. The Indian Meteorological Department recorded 42 tornadoes between 1951 and 1980 (see Table 2-3). They also reported 113 cases of strong winds associated with severe weather events that caused large scale damage. Of the 42 tornadoes, most (33) occurred during the hot season. Many were spawned by nor'westers. The majority (27), as well as the strongest, occurred in Bangladesh and the lower Ganges River basin (see Figure 2-45). They formed near migratory mesoscale lows along wind discontinuity lines in the lower tropospheric levels. The higher incidence of tornadoes in Bangladesh may be due to the many lakes and rivers of that country.

Table 2-3. Monthly Distribution of Reported Tornadoes Between 1951 and 1980.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
0	0	7	17	9	2	1	0	4	1	1	0	42

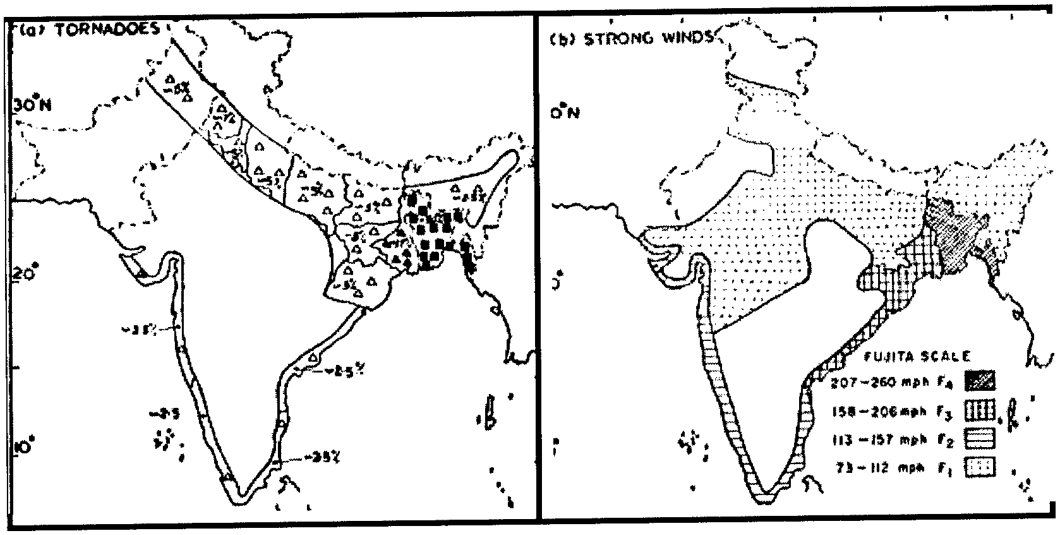


Figure 2-45. Distribution of Tornadoes and Strong Winds over Indian Subcontinent. (Ramage, 1995 adapted from Singh, 1981)

Dust Storms. These are fairly common in the northern part of the subcontinent during the hot season prior to the onset of the southwest monsoon. Conditions become favorable during the long dry season, when vegetation dies and exposes the barren soil. When the hot season sets in, strong, gusty winds pick up the fine, dry soil and carry it to great heights. The Thar desert has the greatest number of dust storms followed by the upper Ganges plains. Once the southwest monsoon sets up and the rains begin, dust storms in the Ganges plains cease. They reoccur during the southwest monsoon if there is an extended break, such as those in El Niño years.

Diurnal Wind Circulations

Land/Sea Breezes. Differential surface heating generates daytime sea breezes and nighttime land breezes along the coasts of India and Bangladesh, however, many of the islands in the region do not have sufficient land mass to generate a land/sea breeze environment. With the monsoon wind reversal, land/sea breeze effects change dramatically from season to season. They are more pronounced during the northeast monsoon (November to May). The marine boundary layer, within which the land/sea breeze circulation occurs, rarely extends above 3,000 feet AGL or beyond 19 miles (30 km) inland unless modified by synoptic flow. Two types of land/sea breezes are described below.

- "Common" land/sea breezes affect many coastal areas of India and Bangladesh. Figure 2-46 illustrates the common land/sea breeze circulation along a uniform coastline under calm conditions with no topographic influences. Onshore (A) and offshore (B) flow intensifies in proportion to the daily heat exchanges between land and water. Common land/sea breezes normally reverse near dawn and dusk, with an onshore sea breeze during the day and an offshore land breeze at night. The sea breeze is at maximum strength during the afternoon.

• "Frontal" land/sea breezes occur when a breeze circulation forms in combination with strong flow perpendicular to the coast. In these cases, a boundary, like that in Figure 2-47, forms. This is often linked to low-level jets, shown as heavy arrows in the figure. Onshore gradient flow enhances the sea breeze; offshore gradient flow strengthens the land breeze and weakens the sea breeze. With offshore flow, the time of the wind reversal is delayed by 1-4 hours as gradient flow keeps the sea breeze boundary layer, or "front," from moving ashore. Under these conditions, the strongest sea breezes occur near midnight, contrary to the norm.

Terrain near the coastline modifies the land/sea breeze in several ways. Orographic lifting produces sea breeze-stratiform/cumuliform cloudiness over higher terrain, while nocturnal downslope winds from the mountains accelerate the land breeze over water. Figure 2-48 shows how the onshore gradient winds and coastal topography affect the land/sea breeze circulation. Onshore gradient flow accelerates orographic lifting by day and enhances cloudiness over ridge tops. It also produces localized cloudiness over the open water during the early morning, due to convergence with the land breeze and downslope flow from the high terrain. Coastal configuration also has an effect on land/sea breezes. Coasts perpendicular to landward synoptic flow maximize sea breeze penetration, while coastlines parallel to flow minimize them.

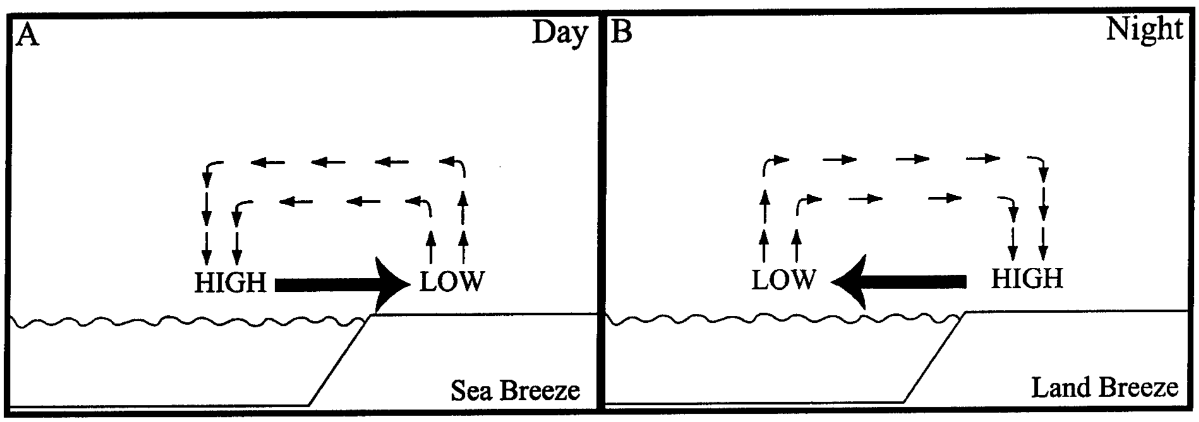


Figure 2-46. The "Common" Sea (A) and Land (B) Breezes. Thick arrows depict the surface flow. Onshore (A) and offshore (B) flow intensifies in proportion to the daily heat exchange between land and water.

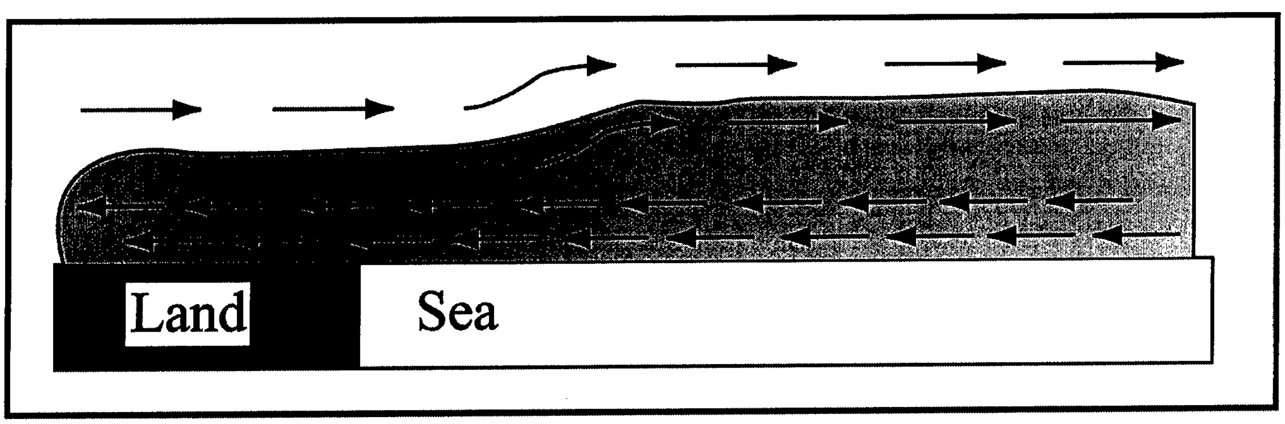


Figure 2-47. A Fully-Formed "Frontal" Sea Breeze. Light arrows depict wind flow; grey-shaded area is the marine air mass; heavy arrows depict low-level jet. Left boundary represents sea breeze "front" onset point.

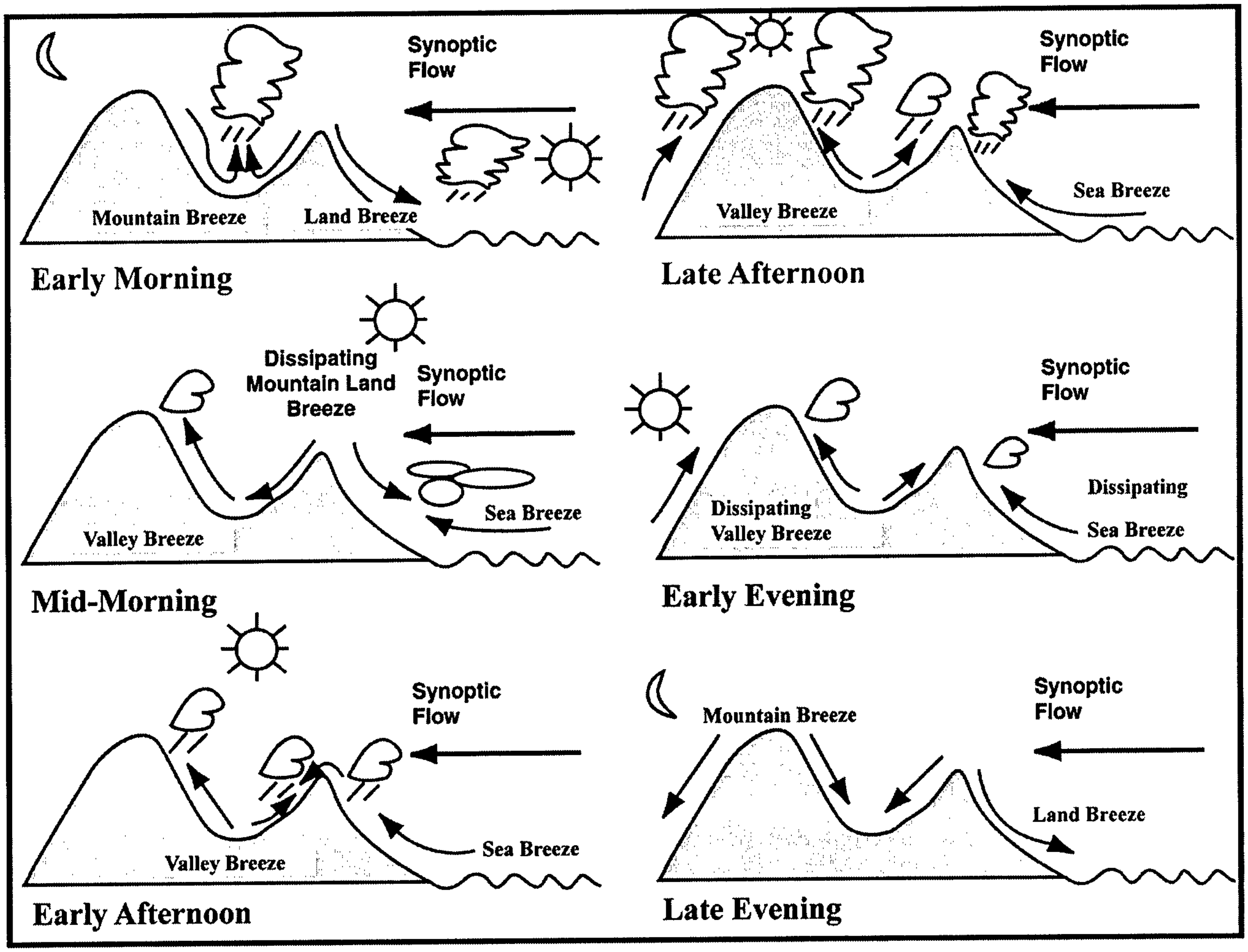


Figure 2-48. Land/Sea Breezes with Onshore Gradient Flow. Topography can lead to localized cloudiness.

Land/Lake Breezes. Several variations of a land/sea breeze circulation are caused by differential heating over large lakes. This circulation occurs in the absence of strong synoptic flow and has a vertical depth of 600-1,600 feet AGL. Figure 2-49 shows an idealized land/lake circulation and its cloud patterns. In the late afternoon (top illustration), a cloud-free lake is surrounded by a 12-24 mile (20-40 km) ring of convection. By early morning, flow reverses and convergence occurs over water.

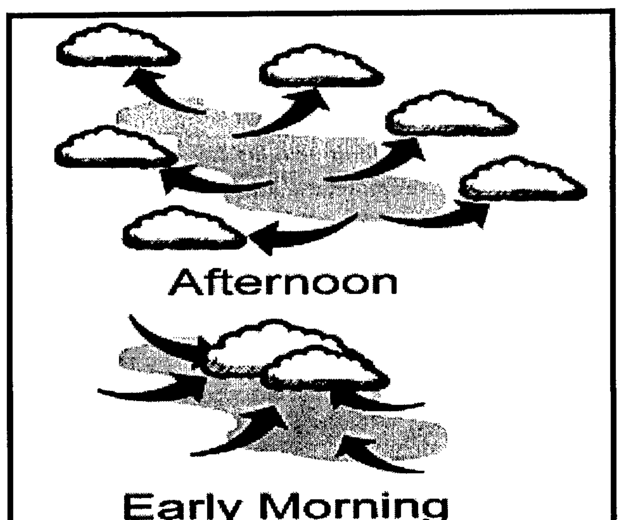


Figure 2-49. Idealized Land/Lake Breezes with Cloud Pattern. Changes in localized convergence leads to changing cloud patterns.

Mountain/Valley and Slope Winds. These winds develop under fair skies with light and variable synoptic flow. Mountain/valley winds, like land/sea breezes, dominate the weather close to the equator, especially when the monsoon is weak. A strong monsoon diminishes these effects, particularly away from the equator. Nocturnal mountain winds that flow toward

the sea are capable of initiating thunderstorm activity, particularly over western Borneo. The two types of terrain-induced winds, valley winds and slope winds, are shown in Figure 2-50 and discussed below. Valley winds tend to be stronger than slope winds and can override their influence.

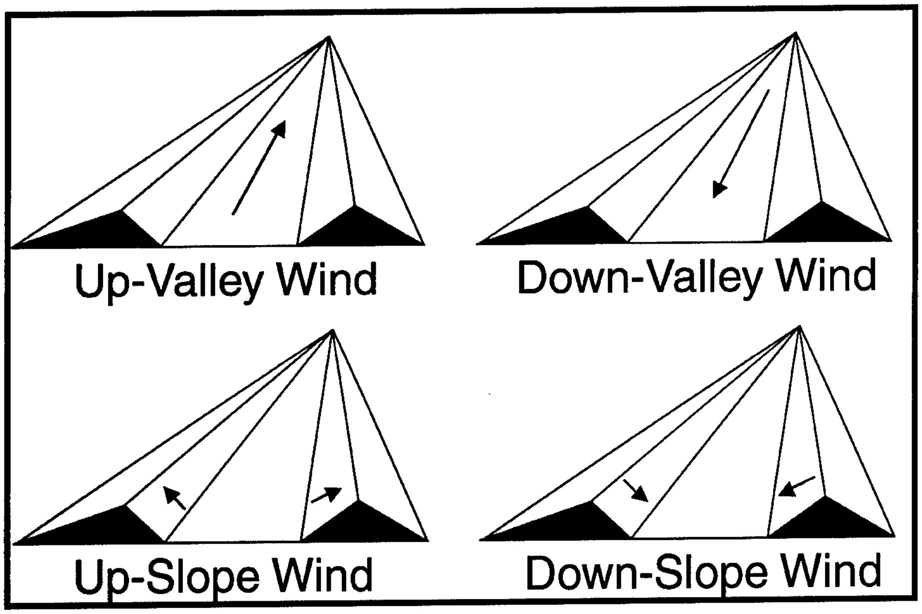


Figure 2-50. Mountain-Valley and Slope Winds. Diurnal temperatures changes trigger these terrain-induced features. The arrows indicate wind flow direction. (Traxler, et al, 1997 from Whiteman, 1990)

Mountain and valley winds develop in response to temperature gradients between mountain valleys and nearby mountains. The air on the upper mountain slopes receive sunlight before the valley floor and consequently heats faster. The resulting upslope winds flow during the day and are strongest in the mornings and weaker by afternoon whenthe temperature is equalized between the mountain slopes and valley floor. The flow reverses at night when the mountain slopes cool faster and cooler air slides downhill. The mesoscale mountain-valley circulation has a maximum vertical extent of 6,500 feet AGL. It is determined by valley depth and width, the strength of prevailing winds in the mid-troposphere (stronger winds produce a shallower circulation), and the breadth of microscale slope winds. These winds can spread their influence into nearby plains areas. Upslope winds during the day pull air into the valleys from the plains and night downslope winds send air pooling out over the plains from the valley. Winds exiting onto the plains are called valley winds. This is generally known as a valley/plain circulation.

Slope winds develop in the surface boundary layer (0-500 feet AGL) of mountains and large hills. Mean daytime upslope wind speeds are 6-8 knots; mean nighttime downslope wind speeds are 4-6 knots. Steeper slopes produce higher speeds. Downslope winds are strongest in the winter and upslope winds are strongest during the summer. Upslope winds are also strongest on slopes that face the sun. Winds from a larger mountain can disrupt the winds of smaller mountains.

Figure 2-51 shows the life cycle of a typical mountain-valley and slope wind circulation. Both valley and slope winds are shown in relation to two ridges (BK and BB) oriented NNW-SSE. Dark arrows show flow near the ground; light arrows show flow above the ground.

These winds are significant in South Asia. Winds of this nature are generally light, although in the Himalayas, downslope winds may be quite violent at times in constricted portions of a valley. During periods of strong pressure gradients, the channeling effect of the valleys may cause strong winds through the mountain passes and in the valleys.

Mountain Inversions. These develop when cold air builds up along wide valley floors. Cold air descends slopes above the valley at 8-12 knots, but loses momentum when it spreads out over the valley floor. Wind speeds average only 2-4 knots by the time the downslope flows from both slopes converge. The cold air replaces warm, moist valley air at the surface and produces a thin smoke and fog layer near the base of the inversion it creates. First light initiates upslope winds by warming the cold air trapped on the valley floor. Warming of the entire boundary layer begins near the 500-foot AGL level.

Mesoscale and Local Effects

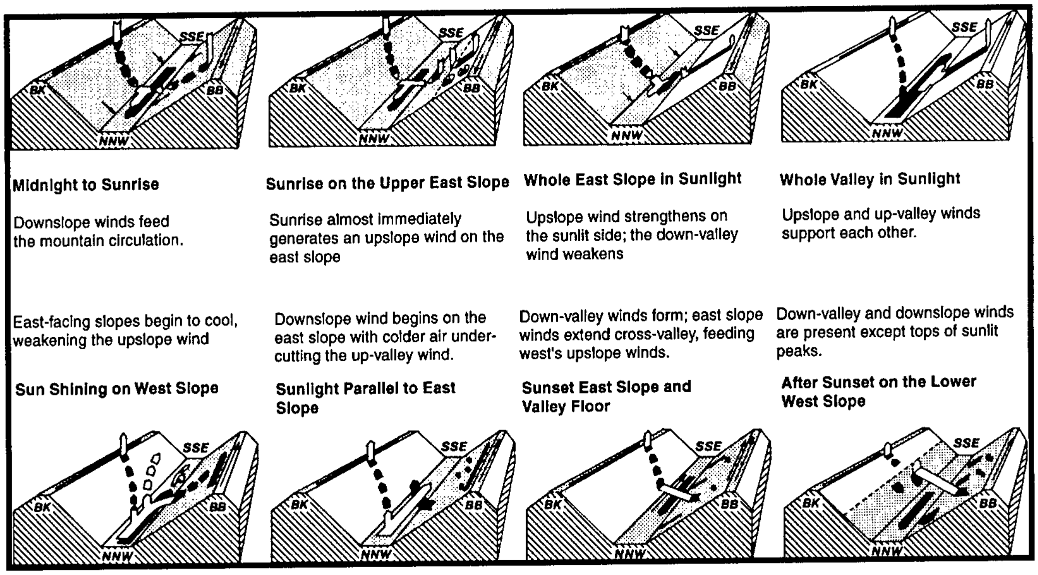


Figure 2-51. Diurnal Variation of Slope and Valley Winds. Both valley and slope winds are shown in relation to two ridges (BK and BB) oriented NNW-SSE. Dark arrows show wind flow near the ground; light arrows show wind flow above the ground. (Traxler, et al, 1997 adapted from Barry, 1991)

Local Wind Systems

Mountain Waves. These can develop when air is forced over the windward side of a ridge. Criteria for mountain wave formation include sustained winds of at least 15-25 knots, winds increase with height, and flow is oriented within 30 degrees of perpendicular to the ridge. The wavelength and amplitude of mountain waves depend on wind speed and the lapse rate above the ridge. Light winds follow the contour of the ridge, with little wave formation. Stronger winds displace air above the stable inversion layer to form waves. This upward displacement of air can reach the tropopause. Downstream, the wave propagates an average distance of 50 times the ridge height. Rotor clouds form when there is a core of strong winds moving over the ridge, but the elevation of the core does not exceed 1.5 times the ridge height. Rotor clouds produce the strongest turbulence. Figure 2-52 shows a fully developed lee wave system.

Foehns. These hot, dry winds occur as air that has been forced over mountain tops descends the leeward slopes adiabatically. Foehn winds are prevalent during the southwest monsoon in Sri Lanka and occur on the lee sides of mountains everywhere. Known locally as kachchan on Sri Lanka, they blow from the central mountains to the east coast. This occurs when the monsoon winds are forced over the mountains and find paths around the mountains. The rising air deposits some of its moisture on the windward slopes and comes down on the other side of the mountain as a hot, dry wind. This wind is usually strong enough to overcome the sea breeze along the east coast.

Jet-Effect Winds. These occur on the downward sides of narrow mountain passes under strong gradient conditions induced by the funneling of the wind. These winds are almost always "supergradient," with speeds as much as 35 to 45 knots higher than prevailing flow. The long, narrow valleys and mountain gaps in the Himalayas are prime locations.

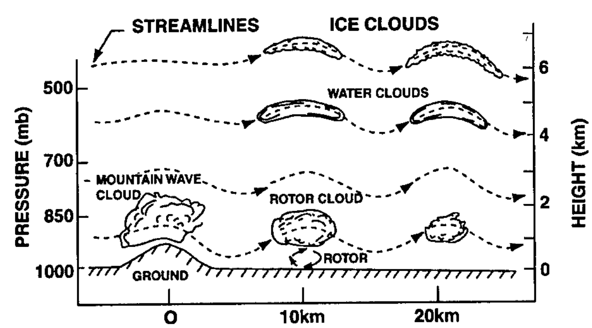


Figure 2-52. Fully Developed Lee Wave System. The figure depicts the features associated with mountain waves including the hazardous rotor cloud located downstream from the wave. (Traxler, et al, 1997 from Wallace and Hobbs, 1977)

Topographical Influences. The major mountains in the north and in peninsular India have a marked influence on the climate of the region. The towering Himalayas prevent the intrusion of cold air from central Asia. The mountains of western Pakistan also shut out much of the cold air. The most profound effect is in the rainfall distribution. The heaviest concentrations are located on the windward side of the mountains and hills, particularly the Himalayas, the Western Ghats, and the Khasi Hills. During the southwest monsoon, the Himalayas force the moisture-laden winds to deposit most of the moisture on the southern slopes. The Himalayas also increase the rainfall in the plains immediately south of the foothills. The area along and just to the south of the Himalayas usually receives 30-60 inches (762-1,524 mm) of rain between June and September.

The Western Ghats, along the southwest coast of India, take the brunt of the southwest monsoon. Orographic lifting of monsoonal flow results in most of the moisture falling on the western slopes. Many sites along the southwestern coast of India have 100 inches (2,540 mm) or more of rain during the southwest monsoon. The area immediately east of the Western Ghats receives relatively light rainfall, even at the height of the southwest monsoon. Typical rainfall amounts in this area are 12-20 inches (305-508 mm).

The southern slopes of the Khasi Hills in northeastern India, are home to the heaviest rainfall amounts recorded. These hills are the first significant terrain features the moist air from the Bay of Bengal contacts. The orographic lifting inundates the southern slopes with heavy precipitation. Most of it falls between March and October, when the southern wind flow is most persistent. Cherrapunji, on a south slope in the Khasi Hills, has nearly 450 inches (11,430 mm) of rain annually because it is at the top of a unique, funnel-shaped valley that faces the Bay of Bengal. Cherrapungi also holds the world record for the greatest monthly rainfall total (366 inches/9,296 mm) and the greatest 12-month rainfall total (1,041.8 inches/26,462 mm). Like the Western Ghats, the valley just to the north of the Khasi Hills sees significantly less rainfall. Amounts are 1/10-1/8 of those on the windward slopes.

Wet-Bulb Globe Temperature (WBGT) Heat Stress Index. The WBGT heat stress index provides values that can be used to quantify the effects of heat stress on individuals. The WBGT is computed using the formula:

$$WBGT = 0.7WB + 0.2BG + 0.1DB,$$

where: WB = wet-bulb temperature
BG = Vernon black-globe temperature
DB = dry-bulb temperature

A complete description of the WBGT heat stress index and the apparatus used to derive it is given in Appendix A of TB MED 507, Prevention, Treatment and Control of Heat Injury, July 1980, published by the Army, Navy and Air Force. The physical activity guidelines shown in Table 2-4 are based on those used by the three services. The physical activity guidelines shown are based on those used by the three services. Wearing body armor or NBC gear adds 6°C to the WBGT, and activity shoud be adjusted accordingly. Figures 2-53a-c gives the average maximum WGBTs for each month of the year. For more information, see *USAFETAC/TN-90/005, Wet Bulb Globe Temperature, A Global Climatology.*

Table 2-4. WBGT Heat Stress Index Activity Guidelines.

WBGT (°C)	Water Requirement	Work/Rest Interval	Activity Restrictions
32 +	2 quarts/hour	20 min/40 min	Suspend all strenuous exercise.
31-32	1.5 quarts/hour	30 min/30 min	No heavy exercise for troops with less than 12 weeks hot weather training.
29-31	1.0-1.5 quarts/hour	45 min/15 min	No heavy exercise for unacclimated troops, no classes in sun, continuous moderate training third week.
28-29	0.5-1.0 quart/hour	50 min/10 min	Use discretion in planning heavy exercise for unacclimated personnel.
24-28	0.5 quart/hour	50 min/10 min	Caution: Extremely intense exertion may cause heat injury.

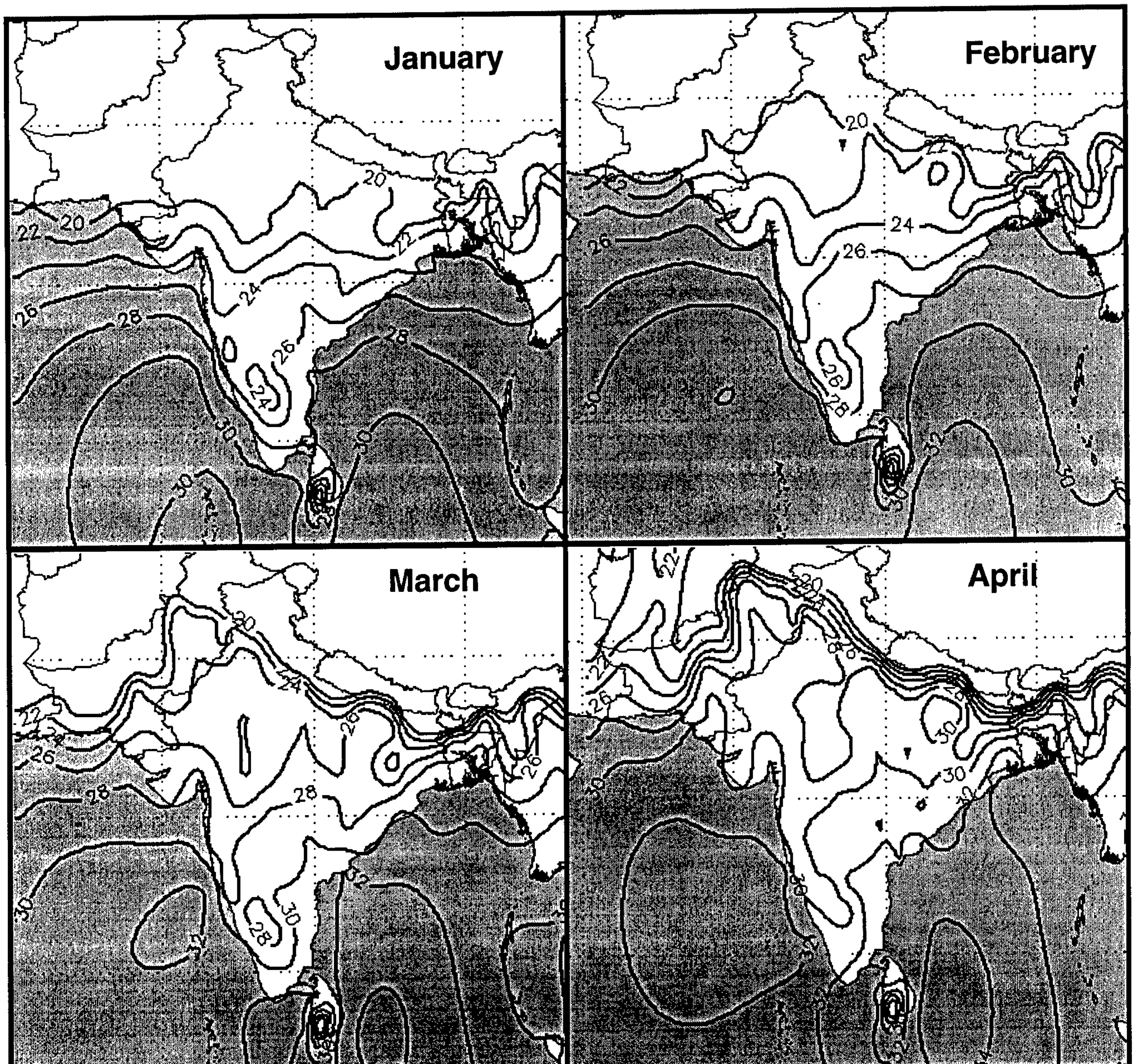


Figure 2-53a. Mean Maximum Wet-Bulb Globe Temperatures (January-April).

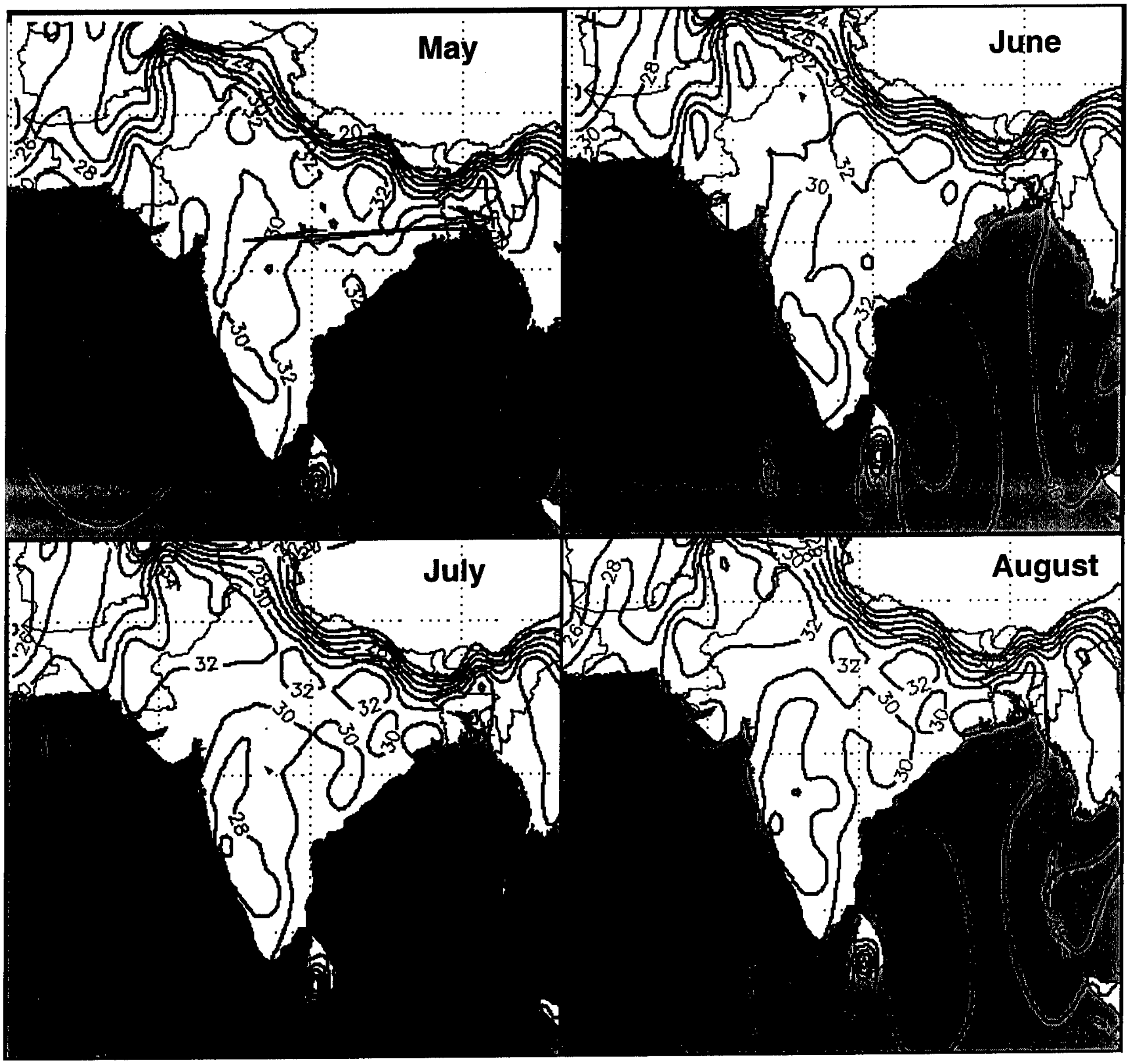


Figure 2-53b. Mean Maximum Wet-Bulb Globe Temperatures (May-August)

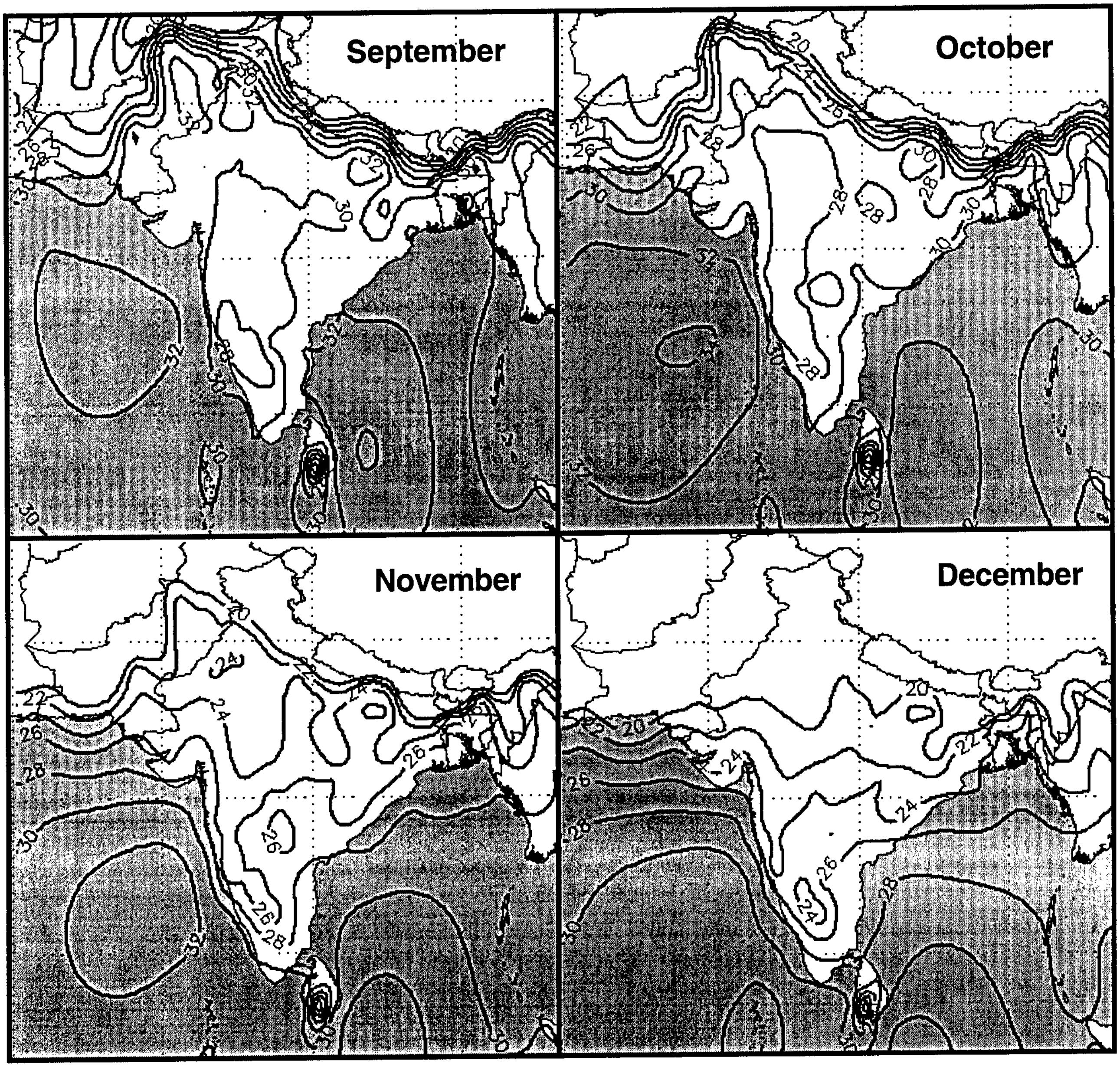


Figure 2-53c. Mean Maximum Wet-Bulb Globe Temperatures (September-December).

Chapter 3

EASTERN COASTAL PLAIN

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for the Eastern Coastal Plain of the Indian subcontinent.

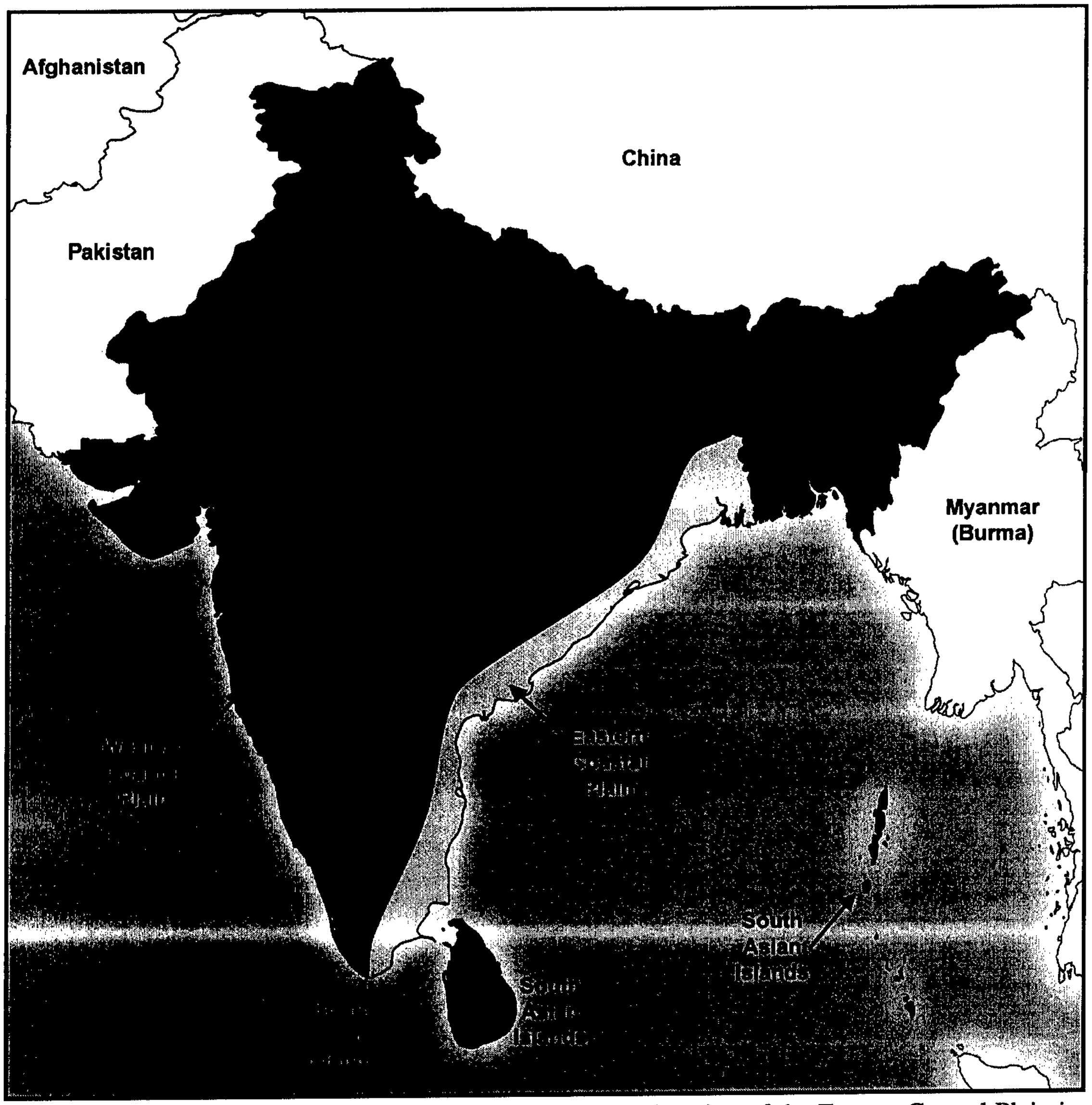


Figure 3-1. Eastern Coastal Plain. The figure shows the location of the Eastern Coastal Plain in relation to the other zones.

List of Topics

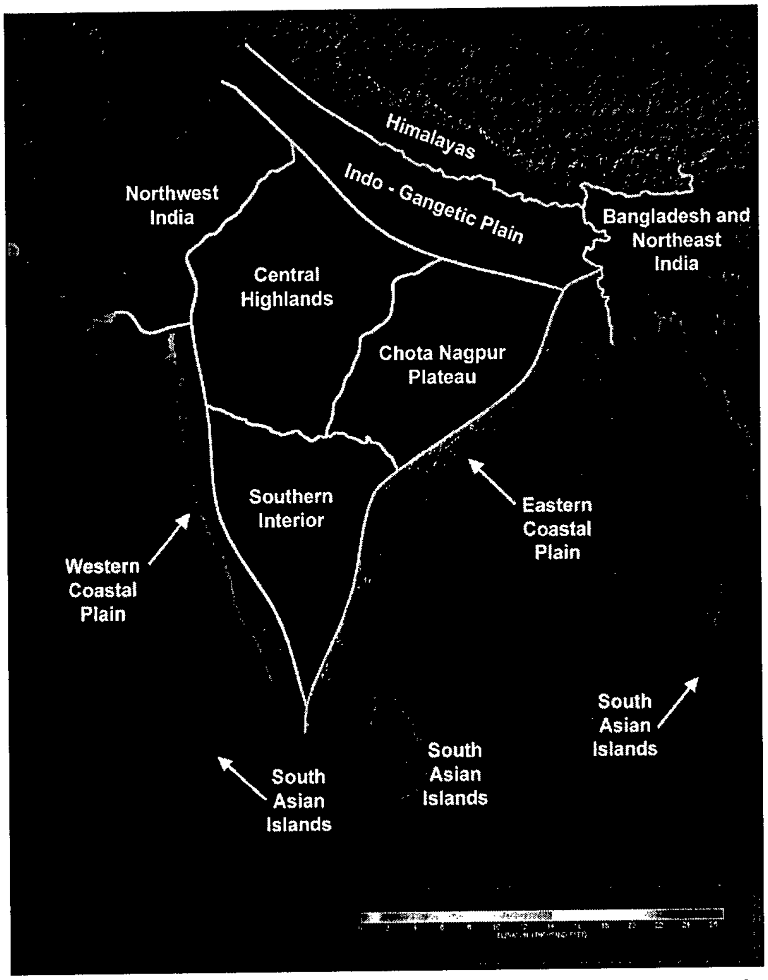


Figure 3-2a. Topographical Map of the Eastern Coastal Plain.

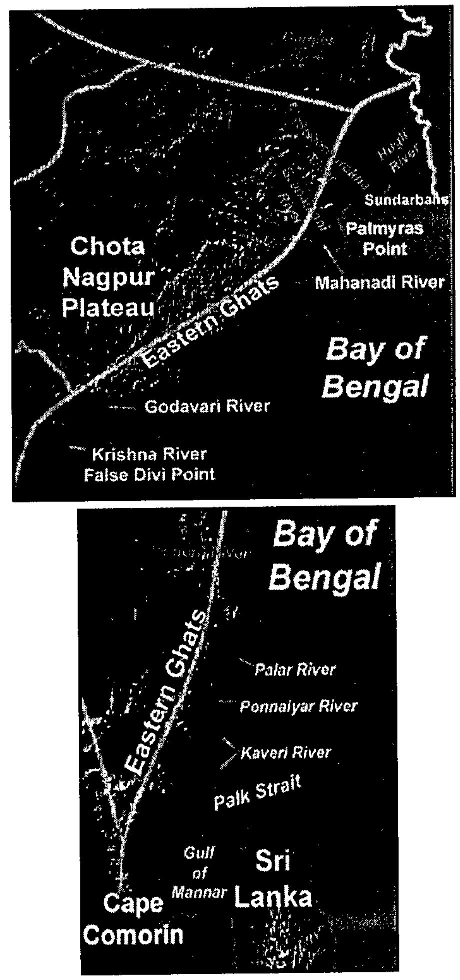


Figure 3-2b. Expanded View of Topography of the Eastern Coastal Plain.

Topography

Boundaries. This area includes the eastern coast of India from Cape Comorin, at the tip of the peninsula, to the Bangladesh border. The boundary of this area follows the Bangladesh border to roughly 24° N and tracks inland to the Chota Nagpur Plateau and the eastern flanks of the Eastern Ghats. East of the Chota Nagpur Plateau, the Ganges basin, which includes most of Bangladesh, begins at the foot of the plateau and extends east to the mountains of northeastern India. The Ganga (Ganges) River and its many branches flow through this broad basin to empty into the Bay of Bengal. The basin is considered part of the lower Indo-Gangetic Plain. The western Bengal basin, in the southwestern corner of the larger Ganges basin, is in the region discussed here. The rest of the coast to the southern end of the peninsula is a narrow coastal plain. It is well watered by many rivers that make their way through the Eastern Ghats.

Mountains. The Eastern Ghat mountains abut this area. They parallel the coast and are heavily dissected with rivers and wide gaps. The mountains, which average 1,500-2,500 feet (450-750 meters) in elevation, gradually taper to the coast. In the lowlands, the elevation is 5-100 feet (2-30 meters). The Chota Nagpur Plateau, north of the Eastern Ghats, is laced with rivers. The average elevation is 2,500-3,500 feet (750-1000 meters) with small areas as high as 4,500-5,000 feet (1,300-1500 meters).

Major Water Bodies. The Bay of Bengal is the main water body. Only the southern end of the peninsula faces into the Indian Ocean. The island of Sri Lanka (formerly

Ceylon) encloses Palk Strait and the Gulf of Mannar at the south end of India. Palk Strait lets out into the Bay of Bengal at the north end and the Gulf of Mannar at the south end. The Gulf of Mannar lets out into the Indian Ocean at its southern end. Although it does not directly face the east coast, the Indian Ocean is a very important moisture source for the area.

Ocean Currents. Ocean currents help determine the regional climate. During the northeast monsoon season, the Bay of Bengal has a clockwise circulation nearly closed to outside flow. During the southwest monsoon, the Southwest Monsoon Current flows from the Arabian Sea and around the tip of the peninsula to feed the clockwise current that circles the Bay of Bengal. The circulation in the Bay of Bengal is more open to water from outside its reaches during the southwest monsoon. The overall water temperature is 77° to 80°F (25° to 27°C) year-round except for the north end of the bay. During the northeast monsoon, it is fed cold water by several large rivers. At the north end of the bay, the temperature averages 75°F (24°C) by January.

Rivers. There are seven major and many minor rivers that empty into the Bay of Bengal through the coastal zone. Rivers flow more or less from west to east either from the Eastern Ghats or through them from the western highlands. The Kaveri (alternately spelled Cauvery) River is the farthest south of the major rivers. It flows via multiple mouths into Palk Strait and the Bay of Bengal. The next large river to the north, Ponnaiyar River, drains to the Bay of Bengal through Cuddalore. The Penneru River empties through Nellore. The Krishna (formerly Kistna) River has many tributaries that join the main river before it flows to many mouths on Point False Divi. The Godavari, a long river with many tributaries, has a huge delta with many outlets to the sea. Masulipatnam and Kakinada (formerly Cocanada) are both in this broad, fertile delta. The Mahanadi (also known as Mahanuddy) flows just north of Bhubaneswar. Like most rivers in this region, it winds and twists through the Eastern Ghats, joins and is joined by other rivers. It is part of a confused maze of rivers and tributaries that drains to the Bay of Bengal via a large, low-lying delta. At the north end of the Mahanadi delta, the Brahamani River empties into the bay at Palmyras Point, and Chilka Lake fills in the south end. The Hugli (also spelled Hooghly) River, nearly 10 miles (16 km) wide at its mouth, is the western-most and most commercially important channel of the great Ganges River. It flows through Calcutta on the way to the massive Gangean delta, known as the Sundarbans, at the north end of the Bay of Bengal.

Lakes. Numerous small lakes and reservoirs pepper the region. Many, especially on the south end of the peninsula, are intermittent. Called "tanks," they fill in the rainy season and slowly evaporate away in the dry months. Lakes near the coast have extensive marshy areas around them; these lakes line much of the coast. There are two large lakes in this coastal region. Pulicat Lake, at 13.5°N 80.2° E, is actually a shallow lagoon separated from the sea by a narrow strip of land. Chilka Lake is a narrow, inland gulf similar to Pulicat Lake. Approximately 26 miles (42 km) south of Bhubaneswar, it is also separated from the bay by a narrow strip of land. It has marshy ground both north and south and backs up to the Eastern Ghats in the west.

Major Climatic Controls

Asiatic High. This thermal high develops over Asia and dominates the weather over the entire continent from November to April. Its vast pool of cold, dry air is a key part of the northeast monsoon in south Asia. Because of the continental source of the air, the weather is dry. The leeside trough on the southern side of the Himalayas, created by flow out of this high, provides a track for storms that move out of Europe on the subtropical jet.

Australian High. This thermal high sets up over Australia during the Southern Hemispheric winter (May through October). It helps smooth the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ), which is a southwest monsoon feature. The outflow from this high also helps to push the equatorial trough (ET) northward to produce the southwest monsoon season in south Asia. This is the rainy season for south Asia.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon (November to April). This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area. This high does two different things based on its strength and position. Although always weak, when the high is at its strongest,

it tends to block low pressure systems from the track across the south foot of the Himalayas by displacing the lee-side trough that is typically in place. Obviously, the farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe that ride the subtropical jet to zip through the region. When the Indian high is weak, it enhances western disturbances.

North Pacific High. This is a major player in the monsoon seasons of South Asia. It shifts north and west in the Northern Hemisphere summer and east and south in the winter. The high is linked to the position of the ET, which, in turn, marks the boundary between the northeast and southwest monsoons.

South Indian Ocean (Mascarene) High. This year-round high-pressure system shifts north and south with the sun. At its strongest during the Southern Hemisphere winter, this high provides cross-equatorial flow from May to October (reflected in both the Somali jet and the equatorial westerlies). This warm, moist flow contributes significantly to the ET shift to the north, which brings the southwest monsoon (and rain) to South Asia.

Asiatic Low. This is a thermal low that replaces the Asiatic high during the Northern Hemisphere summer. The land heats, and the consequent low draws in air. This contributes to the ET shift northward, which brings the southwest monsoon flow to South Asia.

Australian Low. This is a thermal low that develops over Australia during the Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the area of the Bay of Bengal and is a southwest monsoon feature (May to October). Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for the development of monsoon depressions.

Monsoon Climate. For South Asia, the monsoon climate means the subcontinent has a distinct rainy season and dry season. Under the northeast monsoon, the region is largely dry. Under the southwest monsoon, it is rainy. Onset of the rainy season varies by latitude and terrain, but it usually occurs between mid May and late June. Duration of the rainy season also varies widely. In the north, the southwest monsoon season is short; in the southern end of the peninsula, it lasts longer, often twice as long as in the far north. For more details about what constitutes a monsoon climate, read the discussion in Chapter Two.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough in this region, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north, the southwest monsoon takes over in South Asia. When it shifts south, the northeast monsoon assumes control. Chapter 2 offers more details.

Bay of Bengal. This large bay is the primary breeding ground for tropical cyclone storm systems that affect this region. Most of the rainfall in this area occurs from storms that develop or refire over this body of water along the ET, the India-Myanmar trough, or from other mechanisms. The northern half of the bay is more active than the southern half, but storms develop here year-round. The most active times are in October-November (maximum activity) and April-May (secondary maximum). Storms tend to come ashore on the east coast of the peninsula then recurve northward.

Special Climatic Controls

Tropical Easterly Jet (TEJ). This jet exists only during the southwest monsoon season. An upper-level jet that overlays the low-level westerlies, it provides an outflow mechanism for disturbances that develop below it. The heaviest precipitation in South Asia occurs directly beneath the TEJ. The Bay of Bengal and the Arabian Sea are both under the TEJ. The Bay of Bengal is well known to be a prime area for the development or regeneration of monsoon depressions, tropical cyclones, tropical waves, tropical vortices, and mesoscale convective complexes. The TEJ is an important element in the process.

Somali Jet (Low-Level Jet). Also known as the East African low-level jet, this jet exists during the southwest monsoon season and is a key transport for air from the Southern Hemisphere into the Northern Hemisphere. It has been suggested 50 percent or more of the cross-equatorial flow from the Southern Hemisphere into the Northern Hemisphere is moved by this jet. It is created when outflow from the South Indian Ocean high flows toward the thermal low pressure over northern Africa. The western edge of the outflow airmass piles up against the eastern slopes of the high mountains of the eastern African coast. The result of this squeeze is a terrain-induced zone of tight pressure gradient and the jet develops there. The Somali jet is a key element in the development of the equatorial westerlies that dominate the southwest monsoon season.

Equatorial Westerlies. These winds exist during the southwest monsoon season. These large-scale, low-level winds are a result of a combination of factors. Outflow from the South Indian Ocean high (from the southeast) flows toward the thermal low over northern Africa (to the northwest), but the high mountains on the eastern coast of Africa are significant barriers that force a deflection. The Somali jet then helps transport the air into the Northern Hemisphere. The airmass is recurved eastward and these westerly winds take over throughout the monsoon region.

Subtropical Jet (STJ). This jet is significant in this region in the northeast monsoon season when its southern branch slips south of the Himalayas. Low-pressure systems out of Europe (western disturbances) ride the jet through the northern part of India, Bangladesh, and East India. During the southwest monsoon, the SJT is north of the Himalayas.

Western Disturbances. These develop from short waves in the larger, long-wave pattern. They move from west to east and are often most easily observed at 500 mb. In South Asia, particularly in winter, several waves move across the northern portions of the subcontinent and give rise to cloudiness and precipitation. The STJ, south of the Himalayas in winter, provides transport to rapidly move theses waves into and through the area.

Tibetan Anticyclone. This Northern Hemisphere (southwest monsoon) upper-air feature sets up in the zone between the deep easterlies that reach almost to the foot of the Himalayas by July and the deep westerlies of the Northern Hemisphere midlatitudes. Formed above the thermal low of the Tibetan plateau, it is important to the climate during this season because tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. Also, since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought. For a more detailed descriptions, review Chapter Two.

Easterlies. This deep east wind band persists year-round in the low latitudes. It shifts north and south with the sun. During the southwest monsoon, it shifts north and widens to encompass a larger area. Thanks to a number of factors, it also strengthens enough to develop the tropical easterly jet, a broad ribbon of higher winds that strongly influence the development of monsoon rains, tropical disturbances of all intensities, and monsoon depressions. During the northeast monsoon, the band of easterlies narrows and shifts south. At the height of the northeast monsoon, the easterlies are held south of 5° N.

Easterly Waves. During the southwest monsoon season, easterly waves are known to help fire the formation of monsoon depressions over the northern Bay of Bengal. They travel from east to west in the deep easterlies and last 1-2 weeks. They are accompanied by clear weather ahead of the trough and heavy showers and thunderstorms behind. They sometimes create cyclonic vortices off shore the southwestern end of the Indian peninsula and can cause thunderstorms and rainshowers

over Sri Lanka and the southern tip of the peninsula. The intensity and frequency of occurrence of easterly waves are indicators of the strength of the monsoon.

Cyclonic Storms. Monsoon depressions, tropical cyclones, tropical waves, tropical vortices, mesoscale convective complexes, and cloud clusters are all types of cyclonic storms of varying scales of intensity and size. Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Some travel into the area from the west (western disturbances). The ET influences the weather during the transition periods when it moves through the area. During the northeast monsoon, western disturbances and tropical vortices are the bigger players in the development of weather systems. Regardless of when they develop, some storms can be fierce. Because the waters of the bay are so confined, however, storms do not have the opportunity to develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation to the shores of India and Bangladesh, cause extensive flooding and loss of life, and destroy crops and property. Storms tend to come ashore on the peninsular east coast of India then recurve northward. The heaviest precipitation falls in the southwest through south quadrants of the storms.

Monsoon Depressions/Low-Pressure Systems. These are important synoptic-scale disturbances that make major contributions to the monsoon circulation in organizing low-level convergence. During the southwest monsoon season, these storms move along the ET toward the north. They normally form in the Bay of Bengal north of 18° N and move west-northwest across India. They bring heavy rains, especially in the southwest quadrant of the storm. These systems rarely develop into tropical cyclones and are associated with a series of low-pressure systems and easterly waves in the northern Bay of Bengal. The strongest winds are in the southern sector of the storms thanks to augmentation by the equatorial westerlies. Approximately 80 percent of the total number of depressions that form in the South Asia region are monsoon depressions. The majority of monsoon depressions and other cyclonic storms form in the Bay of Bengal as opposed to the Arabian Sea and most of them form in the northern part of the bay.

Land/Sea Breeze. These winds are caused by diurnal land/sea temperature differences. By day, the sea is cooler than land and the wind blows onshore. By night, the temperature difference reverses and the winds become offshore. Onshore winds produce cloud cover and convection over land. During the southwest monsoon, sea breeze winds are augmented by the large scale flow and reach far inland, as much as 100 miles (160 km). This brings moist air well inland to rise up mountain slopes and cause precipitation in the mountains. Offshore winds clear the skies over land by pushing cloud cover out to sea. These same winds can slide convection that developed over the mountains down into the lowlands between them and the sea. Depending on the steepness of the slopes, the downslope flow can create a "front" that fires thunderstorm activity all along the convergence zone between the cool mountain air and the warmer, moist air of the sea. This makes up a line of thunderstorms that marches to the sea over the lowlands.

Nor'westers. These thunderstorms occur in the winter and hot seasons, with most in the hot season. They form in the Bengal basin (the greater Ganges River basin) and frequently develop in the same place at the same time of day several days in a row. These thunderstorms can be extremely violent. They produce high wind gusts, hail, and occasional tornadoes. They develop in the convergence zone between cooler, drier air that flows from the east out of the Brahmaputra River valley around the Khasi Hills and the warmer, moister air from the Bay of Bengal. Once they fire, they spread westward along the collision point between the two air masses.

Hazards for All Seasons

Winter Hazards. The mean freezing level is 13,000-15,000 feet in this season and there is little cloud cover, so icing is not a significant hazard. Turbulence occurs mostly with fronts associated with migratory lows. Over irregular terrain, such as mountains, thermals cause light-to-moderate turbulence up to 10,000 feet in the afternoons. Low-level easterly winds from Brahmaputra River valley flow into the Ganges Plain. Westerlies overlay this surface flow and turbulence occurs in the Ganges plain where the two meet. Nor'westers, in the same area, can become severe enough to produce tornadoes and hail. Although the typhoon season officially ends in November, typhoons have occurred in every month of the year. They bring high winds, huge storm surges, and heavy downpours wherever they make landfall. Amount of damage varies with storm intensity. Violent thunderstorms occur in this season, especially in February. They occur in the Ganges River basin between the Khasi Hills and the eastern flanks of the Eastern Ghats and produce hail, high winds, and tornadoes. They tend to recur in the same place and time of day for several consecutive days.

Hot Season Hazards. The mean freezing level is 15,000-18,000 feet in this season and there is little cloud cover, so icing is not a significant hazard. Nor'westers occur in the Ganges River plain through May and can become severe enough to produce tornadoes and hail.

Southwest Monsoon Hazards. The mean freezing level is 18,000 feet in this season. Multi-layered cloud cover can top 35,000 feet, and icing can be expected through the layer between 18,000 feet and 25,000 feet. Turbulence is mostly with cumuliform cloud formations and thunderstorms. Thunderstorms and/or heavy rains occur just about every day. Just the amount of rain that falls is a hazard because of flooding. The typhoon season is officially from June to November. These storms bring high winds, huge storm surges, and heavy downpours wherever they make landfall. The amount of damage varies with storm intensity.

Retreating Monsoon Hazards. The mean freezing level is 16,000 feet in this season. In the north, cloud cover is diminishing so icing is not a significant hazard. In the central and southern areas, multi-layered cloud cover can top 35,000 feet. Icing can be expected between 16,000 feet and 25,000 feet. Most turbulence in early October is related to cumuliform cloud development and thunderstorm activity. By late October, turbulence associated with the ET occurs. Flooding occurs with heavy rains in south and central areas as November is the rainiest month of the year in those areas. The threat is severely reduced in the northern parts of the area by the end of October. Typhoons bring high winds, huge storm surges, and heavy downpours wherever they make landfall.

Winter

General Weather. In winter, the northeast monsoon dominates. The massive thermal high over Asia is a driving force for pushing the ET south of the equator. The thermal low over Australia helps pull it southward. This is a dry season influenced by migratory low-pressure systems from Europe. These western disturbances bring cloudiness and rain to northern India. The subtropical jet shifts south of the Himalayan massif and pushes these lows along the induced leeside trough at the southern foot of the mountains. The moisture retained after the long trip from Europe is joined by a little moisture from first the Arabian Sea, then the Bay of Bengal as the lows zip through the northern section of India, Bangladesh, and East India. These migratory lows keep northern India cooler and more cloudy than would be expected for mostly offshore flow. The storm track along the foot of the Himalayas exists from December to March and is at its southern-most position at the end of the season. It vanishes entirely by late March. The deep band of easterlies that dominate upper-air flow in the southwest monsoon are held south of 5° N and do not influence the weather in this region nearly as much as the westerlies that take over in this season.

Onset of the northeast monsoon, or winter, season is at a different time within a general frame that depends on latitude and terrain. The ET retreat southward marks the onset on the season. Obviously, it occurs first in the north and last at the south end of the peninsula. Usually, the ET has moved south of the north end of the region (Calcutta and the rest of the west Bengal basin area) by the middle of October. It does not move south of the southern tip of the area, the Palk Strait/ Gulf of Mannar area, until the end of December. The northeast monsoon brings northerly winds to the north parts of this region and northeasterly winds to the southern part of the peninsula. These winds bring rain to the southeastern coast of the peninsula.

Tropical cyclones and other cyclonic storms are less likely in this season than during the southwest monsoon; however, the storm season extends to November. The transition periods in October-November and in April-May, when the ET moves through the Bay of Bengal, is when the cyclonic storm occurrence rates peak. Although the rate drops off sharply after November, there is an incidence of at least once storm in every month of the year. The minimum number occurs in February, when the northeast monsoon is at its greatest strength.

Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Western disturbances, easterly waves, and vortices also grow into storms over the warm waters of the bay. While some of these factors have a greater influence during the southwest monsoon season, such as easterly waves and the India-Myanmar trough, the early and late parts of the northeast monsoon season still experience weather stirred by them. Regardless of when they develop, the storms can be fierce. These storms do not develop the power of open ocean tropical cyclones because the waters of the bay are so confined. Still, they carry vast amounts of precipitation to the shores of India and Bangladesh, cause extensive flooding and loss of life, and destroy crops and property. Storms that develop in this season are most likely to strike the southern tip of the eastern peninsular coast.

Although more frequent in the hot season, Nor'westers occur in winter, especially in February. These often violent storms recur in the same place at the same time of day for several days in a row. They most often occur in the afternoon, but have occurred in morning and evening hours as well. These storms produce high winds, hail, and occasional tornadoes. They occur in the Ganges River basin from the west end of the Khasi Hills westward.

Sky Cover. The southern parts of the area have broken cloud cover early in the season, but this decreases to scattered by the end of December. In the north half, cloud cover averages scattered all season. Broken-to-overcast cover occurs 4-6 days per month in the north, usually with middle and high cloud ceilings. Clear or scattered-cloud days average 24-26 per month. Broken-to-overcast cloud cover occurs in the south 8 days per month except from Negapatam to Nellore. This area has more cover because of the nearly direct onshore flow under the northeast monsoon. Cloud cover is broken to overcast 11-15 days per month. Most cover is middle and high cloud.

Ceilings below 5,000 feet occur under 5 percent of the time in most of the region (see Figure 3-3). The exception is in the Negapatam to Nellore area where they occur 15-25 percent of the time in December and January. There is little diurnal difference. In February, the rates there drop to 10 percent of the time. Ceilings

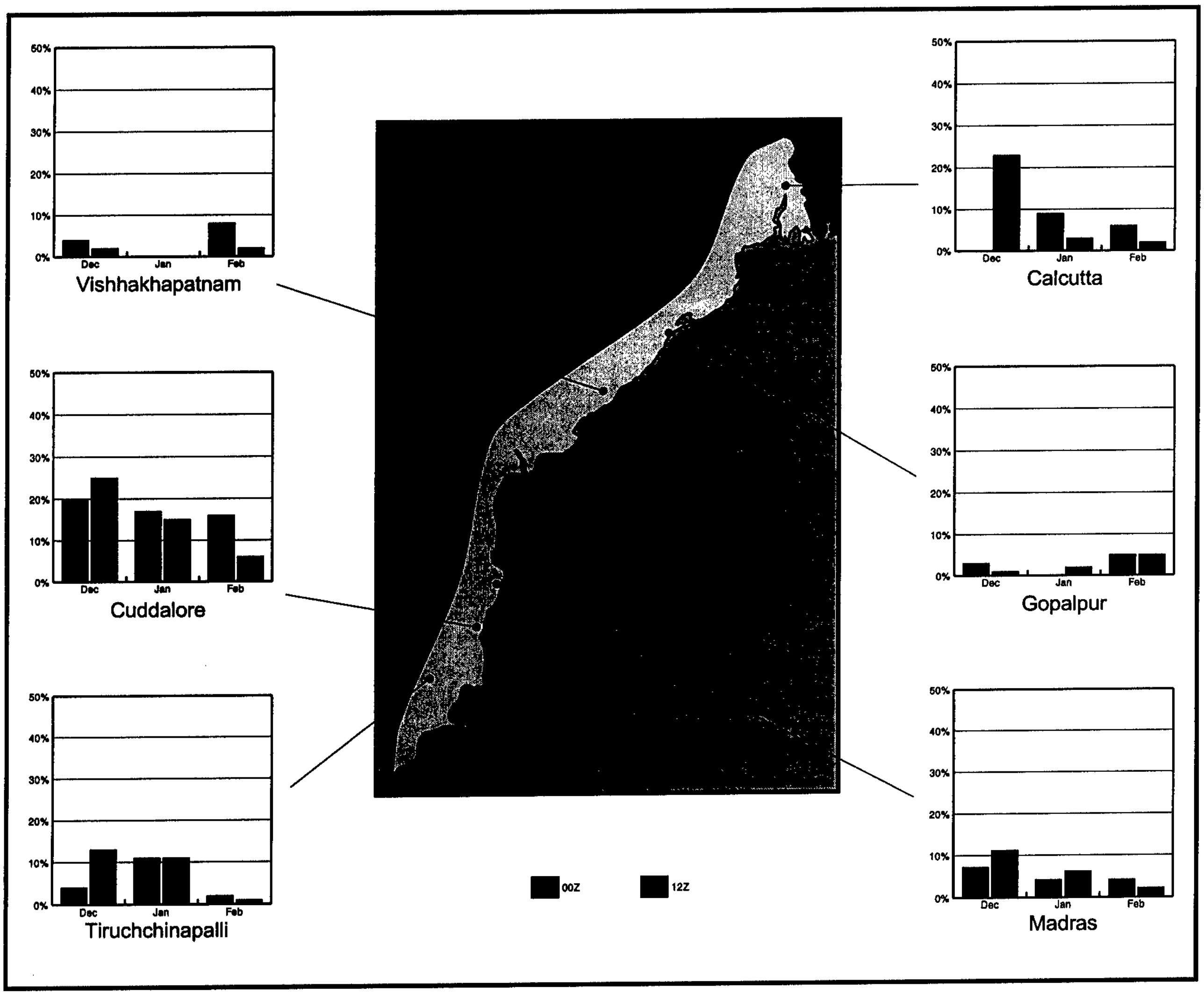


Figure 3-3. Winter Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

below 1,000 feet are very rare.

Visibility. Visibility is generally fair even though smoke and haze tend to worsen as the season progresses. Visibility conditions are best in December and worst in February. The best visibility of the day occurs in the afternoons, the worst at sunrise. Visibility below 6 miles (10 km) occurs 80-100 percent of the time at sunrise. The fog burns off, and the rate tapers by noon to under 20 percent of the time in small towns and rural areas and 40-50 percent of the time in bigger cities.

Visibility below 2 1/2 miles (4,000 meters) occurs far less often, under 5 percent of the time at sunrise and not at all after that in most places (see Figure 3-4). A few coastal cities near marshes or lakes have visibility below 4,000 meters 10-15 percent of the time at sunrise with fog that burns off quickly within an hour or two. Gopalpur, just south of Chilka Lake, has visibility below 4,000 meters 12 percent of the time in January and February at sunrise and rarely the rest of the day. Very large, heavily populated cities, such as Calcutta, have visibility below 4,000 meters up to 65 percent of the time at sunrise. Smog delays improvement to midmorning. After that, visibility below 4,000 meters occurs under 10 percent of the time in large, urban centers. Visibility below 1 1/4 miles (2,000 meters) rarely occurs at any time of the day. Large urban centers get it as much as 20 percent of the time at sunrise and rarely after that.

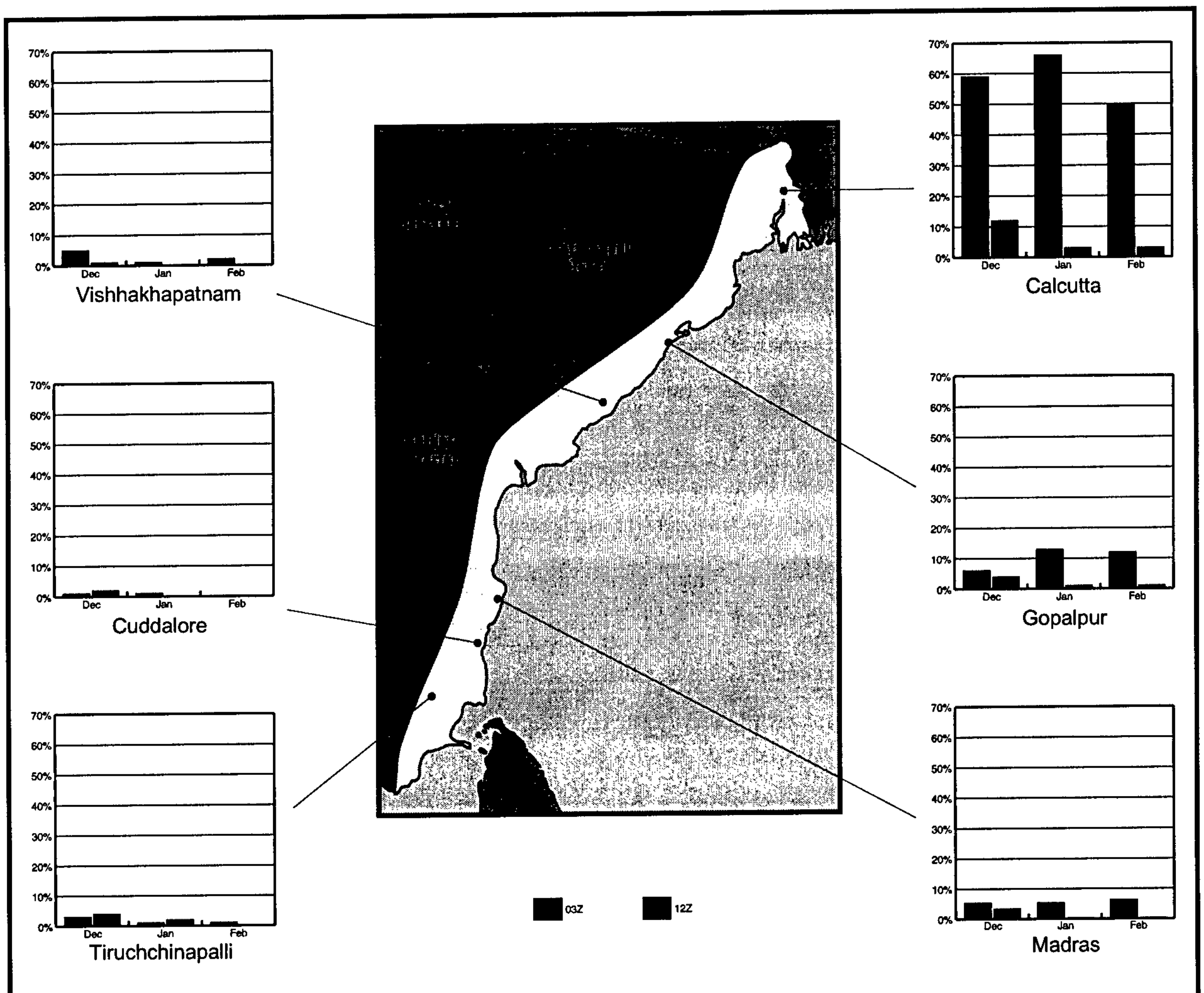


Figure 3-4. Winter Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The winds are light and northeasterly for this area with a sea breeze influence close to the coast. The sea breeze is augmented by prevailing northeasterly flow and the land breeze at night is damped by it. The Eastern Ghat mountains create upslope-downslope winds at their feet, which affect diurnal wind direction and speed in their vicinity. In the north, winds are generally from the north at 5-10 knots. Calcutta and Sandheads both have north winds at 5-10 knots. In the central areas, winds are mostly northeasterly at 5-10 knots; a few places have winds up to 15 knots. Cocanada gets sea breeze winds from the southeast at 5 knots during the afternoon and northeast winds at 5 knots the rest of the day. Vishakhapatnam gets northeast winds at 10-15 knots all day. In the south, most places get northeast winds at 5-10 knots all days. A few sites get as much as 15 knots. Nellore has winds from the northeast at 5 knots most of the day with southeast winds at 5 knots in the afternoons. Cuddalore has northeast winds at 5-10 knots all day. Maximum speeds outside of typhoons near 30 knots everywhere. See Figure 3-5 for representative stations.

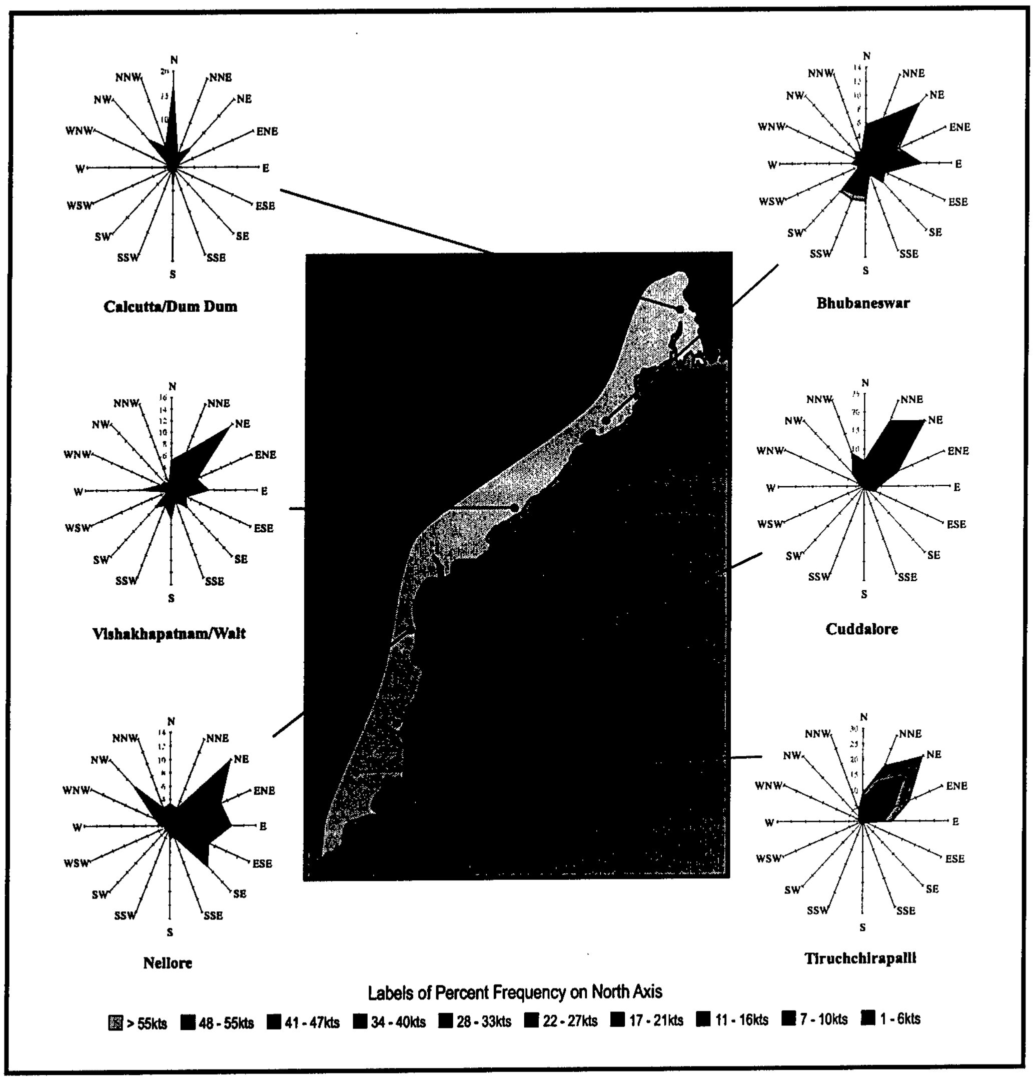


Figure 3-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. December 850-mb winds vary from northwesterly at 10 knots in the north to easterly at 10 knots in the south. In the central areas, winds are variable at 10 knots. In January and February, they are northwesterly at 10-15 knots in the north and northeasterly at 5-10 knots for the central and southern areas. From December through February, the 700-mb winds are westerly at 15-20 knots in the north and easterly at 5-10 knots in the rest of the region. At 500 mb, westerly winds dominate the season. In the north, they are 40 knots. In the central and southern areas, they are only 10-15 knots. Westerlies continue to rule at 300 mb; they are at 70-75 knots in the north and 25-30 knots in the central and southern areas. In the north, the subtropical jet averages 95-105 knots at 200 mb. Calcutta upper-level winds are shown in Figure 3-6.

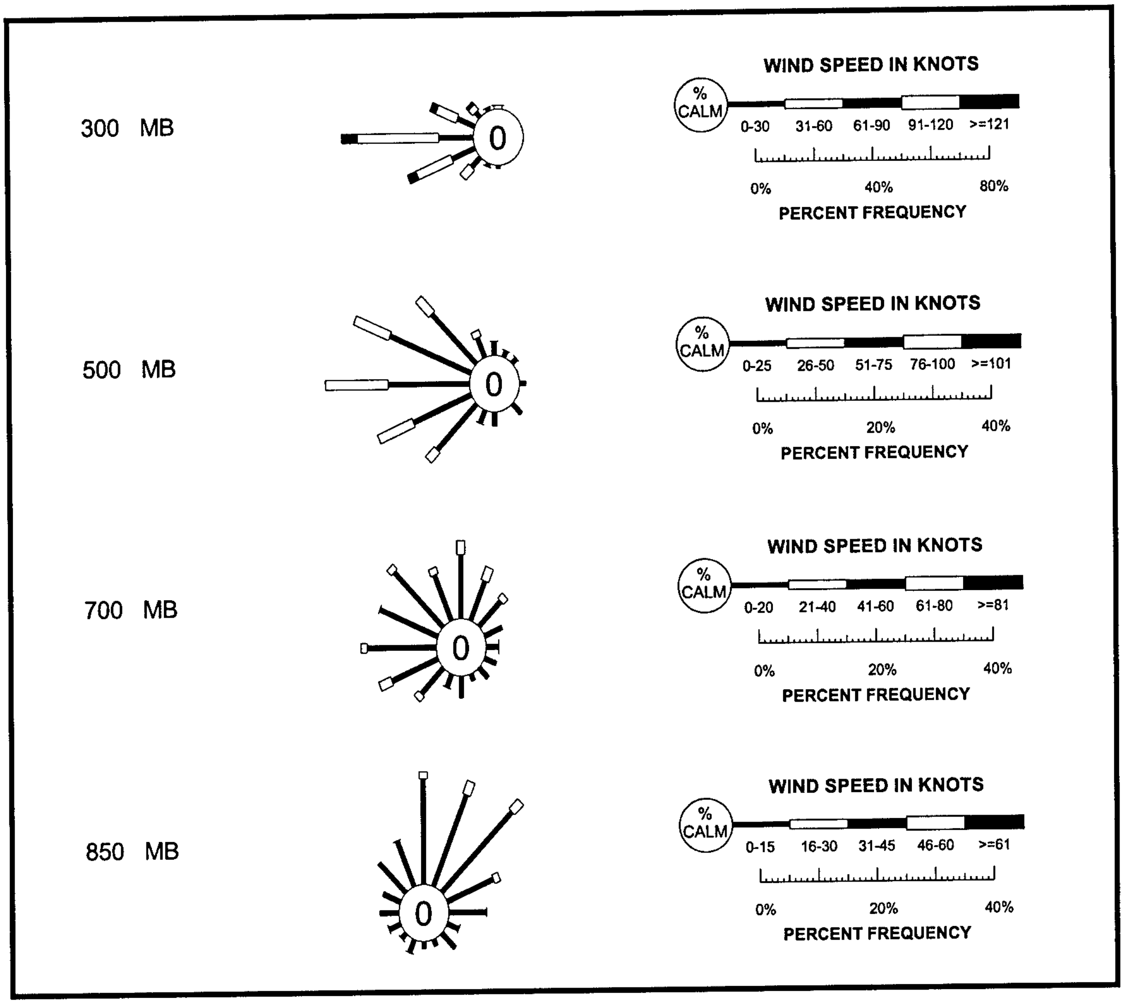


Figure 3-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Calcutta.

Precipitation. Early in the season, the retreating ET drops considerable rain in its vicinity. The southern coast can get 4-10 inches (102-254 mm) of rain, generally with west-moving tropical disturbances; southernmost sites get the most. The highest amounts occur on the windward slopes of the mountains at the western edge of the coastal plains. Once the ET moves south, very light precipitation, under 1 inch (25 mm), occurs per month. There is an exception. From Negapatam to Nellore, in the south, prevailing (northeast) winds are almost directly onshore after a long trajectory over the Bay of Bengal. Here, 2-3 inches (51-76 mm) of rain fall every month. The northern areas get under 1 inch (25 mm) of rain per month all season.

Precipitation occurs 1-3 days per month in the north half of the region all season and throughout the region in January and February. In the south, December gets 3-9 days with rain with the most in the Negapatam to Nellore area. After December, conditions dry sufficiently to drop the rain days to the norm. Thunderstorms occur less than 3 days per month everywhere. In the northern three-quarters of the region, most places have less than 1 thunderstorm day per month. Only the southernmost tip of the peninsula has more, 2 days per month. In the northern Ganges River basin, Nor'westers are possible. See Figures 3-7 and 3-8 for precipitation amounts and thunderstorm and rain days.

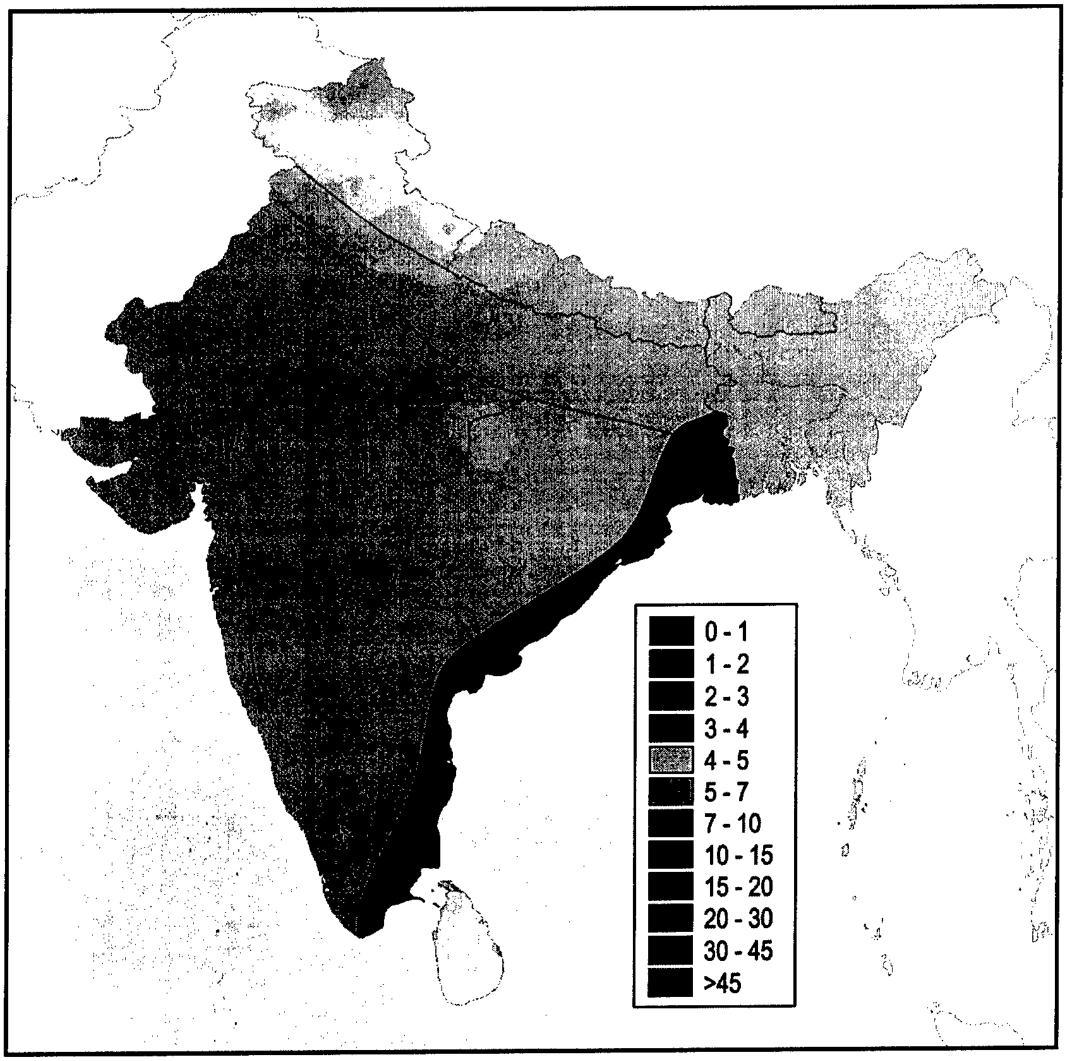


Figure 3-7. January Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

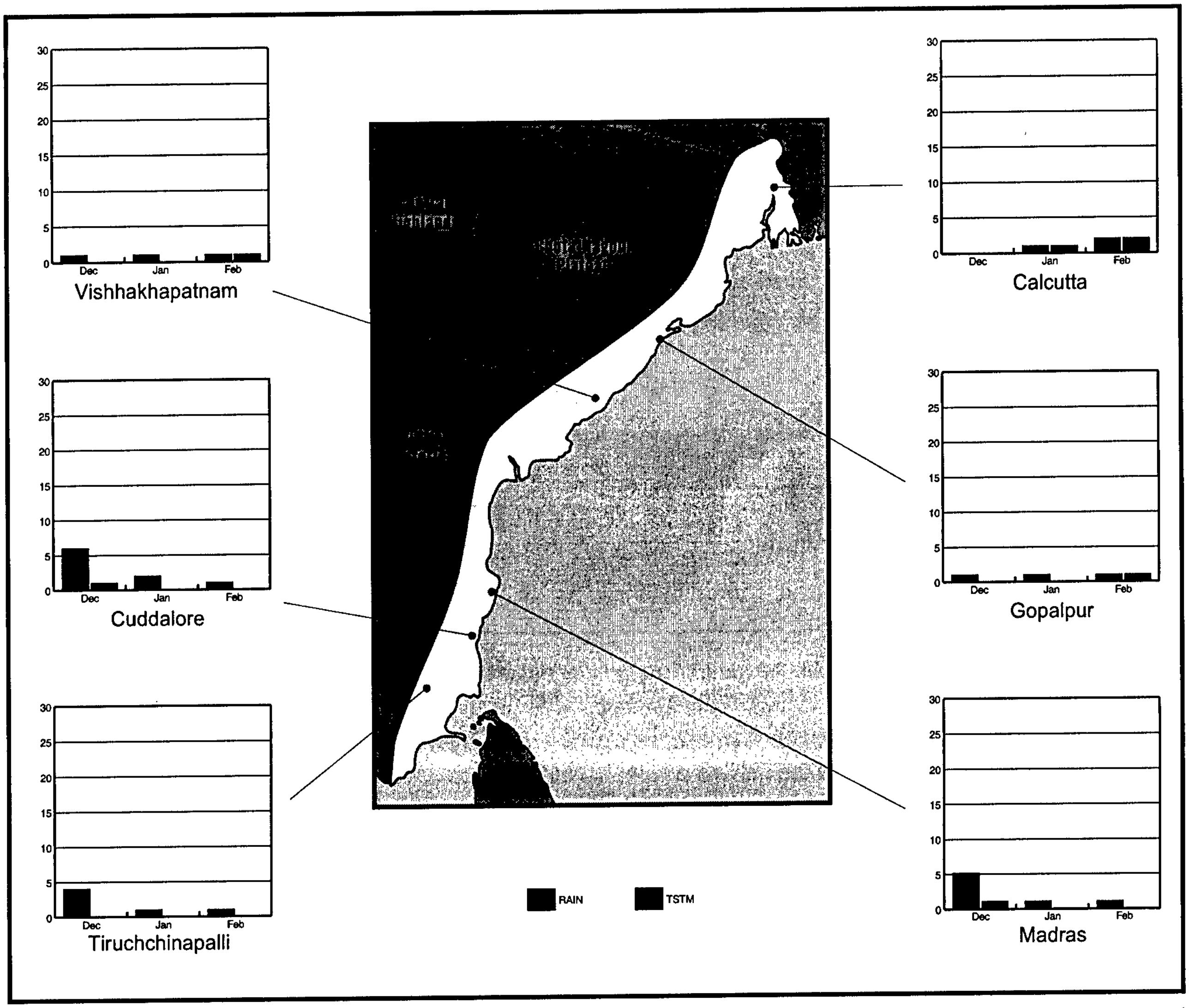


Figure 3-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. February is the warmest month of the season although there is little variation between the months. For most of the area, mean highs range from 81° to 86°F (27° to 30°C) and mean lows range from 66° to 72°F (19° to 22°C). Temperatures are cooler in the north. The diurnal range is larger inland than on the coast. Mean highs range from 74° to 78°F (23° to 26°C) inland to 81° to 85°F (27° to 29°C) on the coast. Mean lows are 54° to 58°F (12° to 14°C) inland and 63° to 68°F (17° to 20°C) on the coast. Extreme highs are 97° to 100°F (37° to 38°C), and extreme lows are 50° to 57°F (10° to 14°C). Figures 3-9 and 3-10 show the mean maximum and minimum temperatures for January.

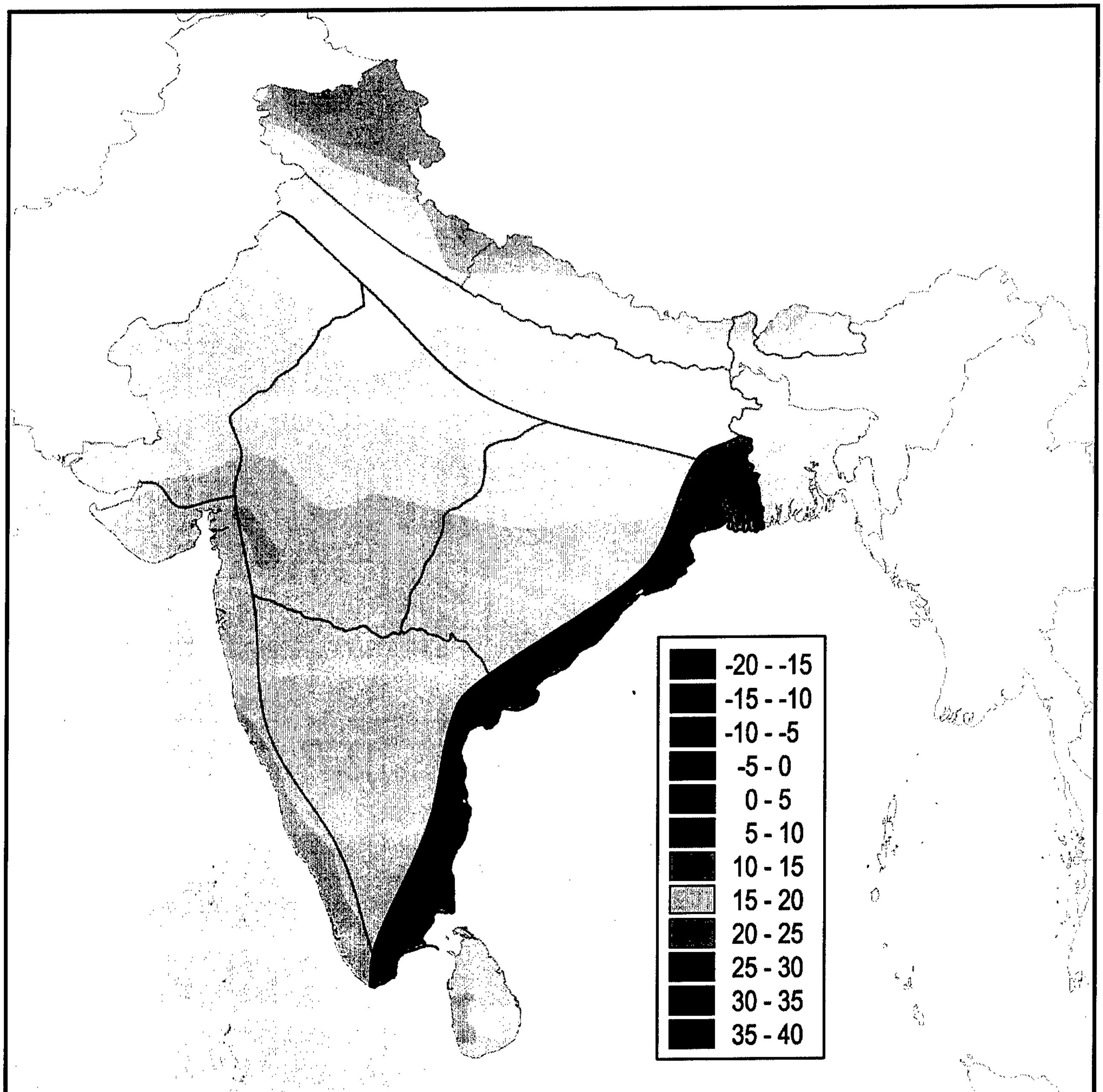


Figure 3-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in January. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other winter months may be higher, especially at the beginning and ending of the season.

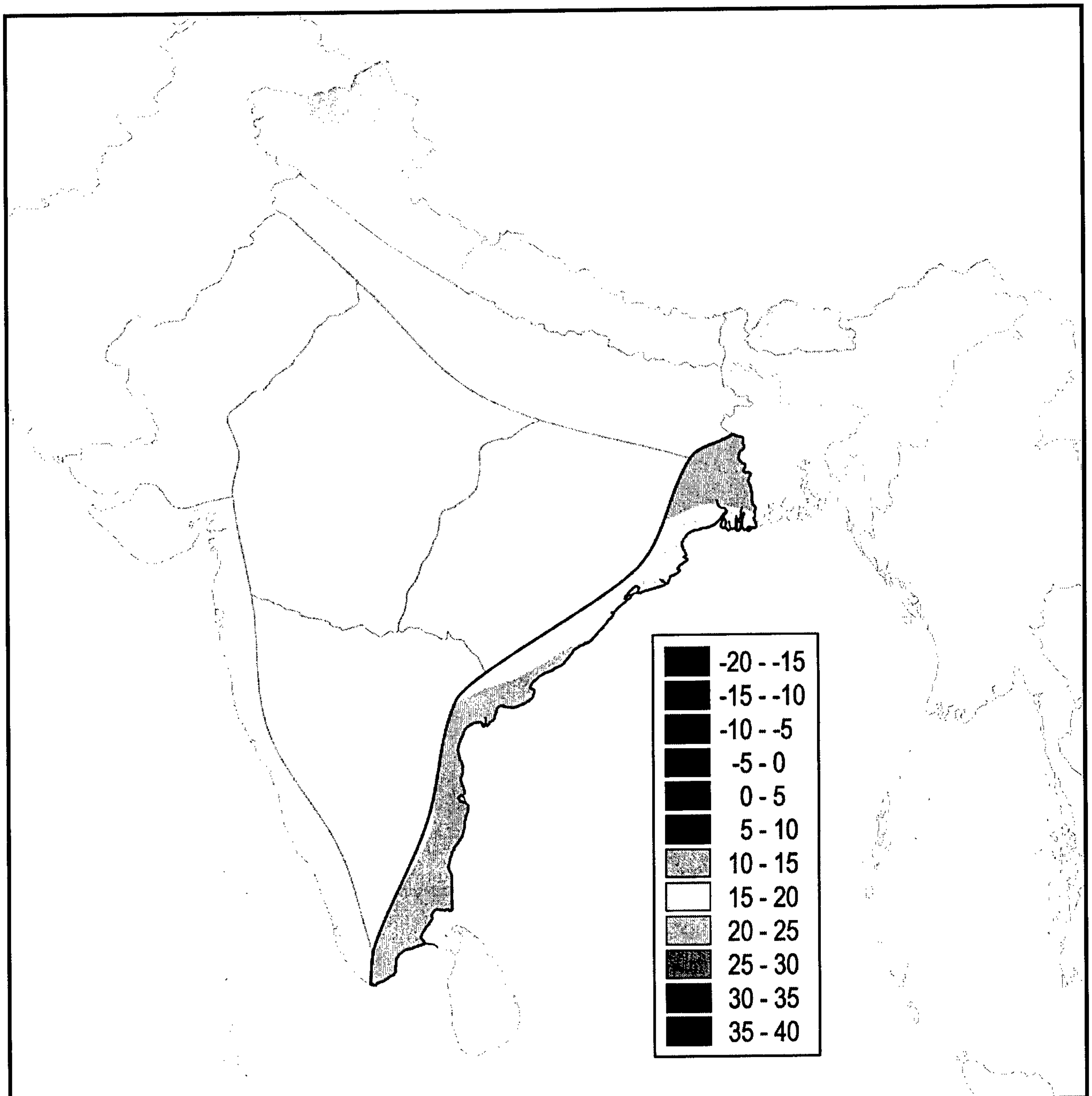


Figure 3-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in January. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other winter months may be higher, especially at the beginning and ending of the season.

Hot Season

General Weather. This is when the dry weather reaches its peak. The subtropical jet that moved migratory lows through in the winter now lies mostly north of the Himalayan massif. Also, the thermal high over Asia is seriously weakened by March, and the induced leeside trough at the southern foot of the mountains is no longer a favored track for passing lows (western disturbances). This moves the storm track from the southern flanks of the Himalayas to north of the range, and few lows move across northern India as a result. The thermal low over Australia disappears, and the equatorial trough heads north with the sun. Wind circulation is confused. All in all, the weather is clearest and driest in these months, and the hottest temperatures occur.

April to May is when the ET crosses over the southern part of the peninsula at the leading edge of the southwest monsoon airmass. There is considerable variance in onset of the southwest monsoon across the region. The rains begin at almost the same time on the southern tip of the peninsula and in the northeast corner of the Bengal basin to Assam (East India) in mid-May. It takes another month and a half for all of India to be fully under the southwest monsoon regime. The northward travel of the ET is not a smooth, steady one. It oscillates north and south, moves many miles in surges then retreats, and stagnates in one place for days at a time. In this transition season, "onset vortices" travel along the ET at the leading (northern) edge of the southwest monsoon airmass. These vortices produce rain, rainshowers, and thunderstorms and signal the "monsoon burst" of the changing season. The hottest weather of the year ends with this transition. Although not common, tropical cyclones do develop in the Bay of Bengal in the hot season. Their mean track brings them ashore in the area of Bhubaneswar, on the northeastern coast. They are more likely to occur in May, with the equatorial trough as it shifts north, than in April.

This is the season Nor'westers are most common. They occur in the Ganges River basin between the western end of the Khasi Hills and the eastern flanks of the Eastern Ghats. These violent storms form in the convergence between cooler, drier flow from the Brahmaputra River valley and the warmer, more moist flow of the Bay of Bengal. They often recur in the same place at the same time of day several days in a row, most often in the afternoons. They can produce hail, high winds, and occasional tornadoes. They disappear once the southwest monsoon begins.

Sky Cover. Cloud cover is at its minimum in the early half of the season but increases as the ET approaches. In March and April, clear skies dominate, but progressively more cloud cover moves in by mid-May as the ET approaches. Conditions in the north remain mostly scattered through the end of May. Only 3-6 days have broken-to-overcast clouds in March and April. After that, the northern areas vary from scattered to broken over the course of the day with the most cloudiness in the morning hours. In May, the northern area has 8-10 days with broken-to-overcast cover. Mostly scattered cloud dominates the southern areas in March and April, but cloud cover increases to broken by mid-May as the ET approaches. In March and April, broken-to-overcast sky cover occurs 3-7 days per month. In May, it jumps to 12-16 days.

Middle and high cloud dominate. Lower clouds mainly occur with organized weather systems and thunderstorms. Ceilings below 5,000 feet occur least in March and most in May. They also occur more in the south than in the north, except in May, when ceilings in the northernmost part of the region get a jump in cloud

cover as the monsoon rains begin. Diurnally, morning has the highest rate of ceilings and afternoon to evening has the lowest.

In the northernmost areas, May ceilings below 5,000 feet occur up to 26 percent of the time. March and April ceilings in that area drop below 5,000 feet 15-20 percent of the time. In the south, ceilings below 5,000 feet occur under 5 percent of the time in March mornings, and under 10 percent of the time in April and May mornings. From Cuddalore on south, ceilings below 5,000 feet occur 24 percent of the time in May mornings. By afternoon, most places show a drop in occurrence rates to under 5 percent of the time even in the southernmost places. Masulipatam, halfway up the eastern coast, has ceilings below 5,000 feet 15-25 percent of the time between 0800 and 1300L because of fog lifting off surrounding rice paddies to form ceilings that break up by early afternoon. The rest of the day, they follow the rest of the area. Ceilings below 1,000 feet rarely occur any time of the day anywhere in the region. See Figure 3-11 for occurrences of ceilings below 5,000 feet.

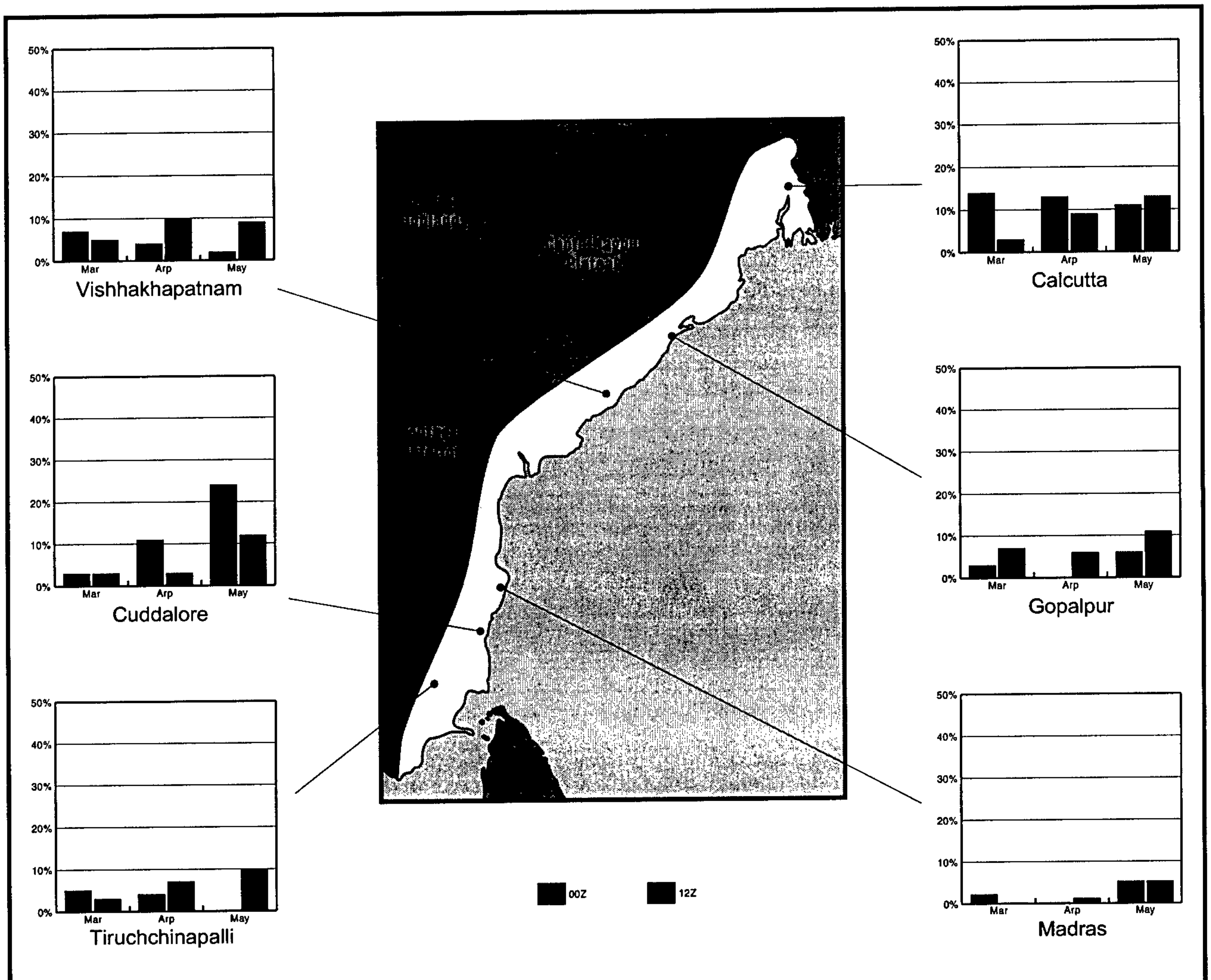


Figure 3-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility remains fair through the season but is at its worst of the year as more and more haze, dust, and smoke are suspended in the air. The lowest visibility of the day occurs in the morning and the best in the afternoon. Visibility below 6 miles (10 km) occurs 80-100 percent of the time at sunrise, begins to improve by midmorning, and drops to under 5 percent of the time by noon. It remains low the rest of the day. A few places have lingering fog and haze. These are commonly very close to the coast in low-lying areas with extensive rice paddy cultivation around them. Gopalpur is a good example of this. Visibility remains below 10 km 90 percent of the time at sunrise, 65 percent of the time to mid-morning and 20 percent of the time through the remaining daylight hours. Once the sun sets, the rates rise to 65 percent of the time after 1800L and again to 80-85 percent of the time soon after midnight.

Visibility below 2 1/2 miles (4,000 meters) occurs far less often (see Figure 3-12). In most places, it occurs rarely even at sunrise. In places like Gopalpur, it occurs 15-20 percent of the time at sunrise and up to 10 percent of the time the rest of the day. Visibility below 1 1/4 miles (2,000 meters) rarely occurs anywhere in the region.

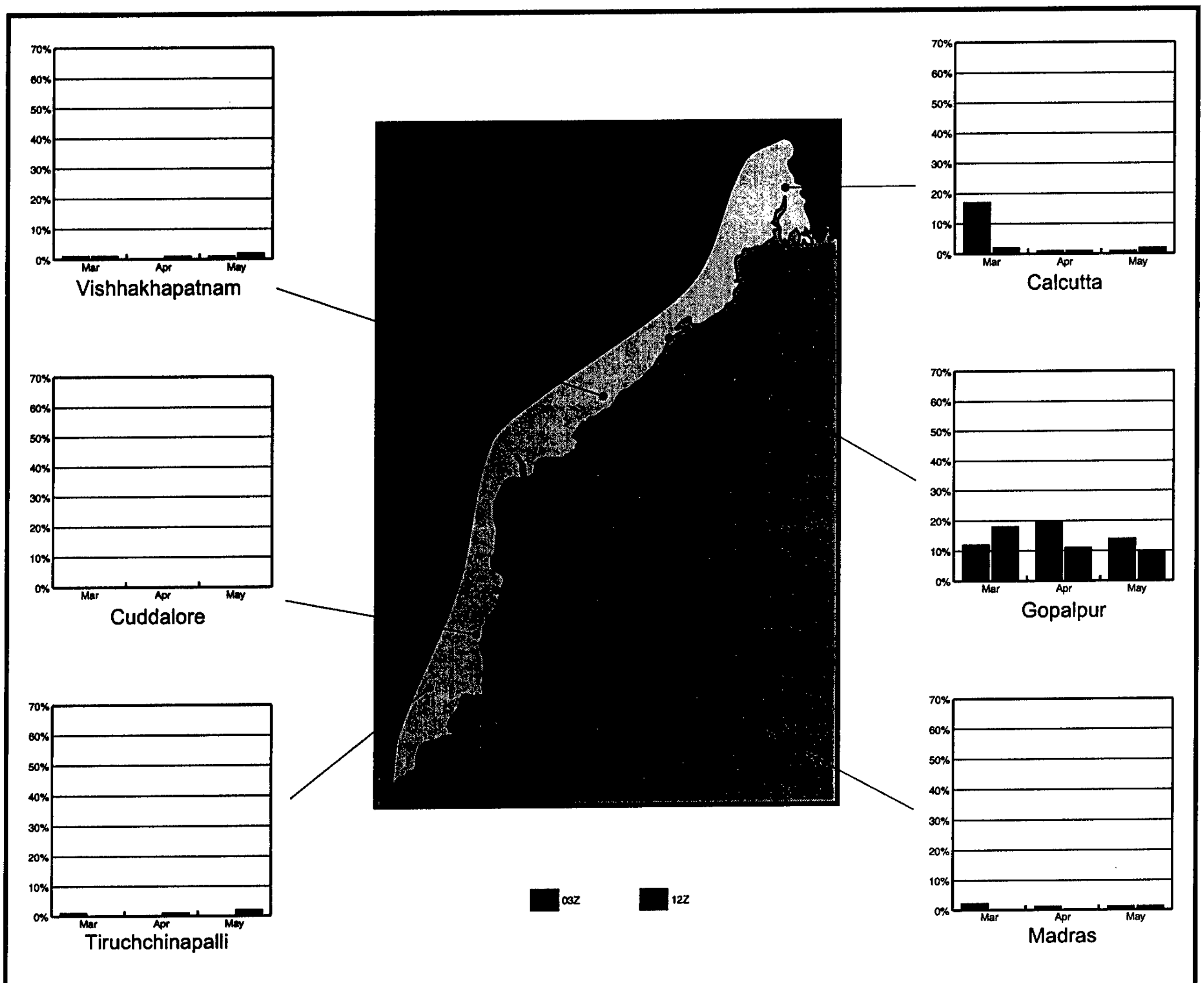


Figure 3-12. Hot Season Percent Frequency of Visibility below 21/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Flow begins the season light from the northeast. Land/sea breezes are at their annual strongest. Most places have switched over to southeast to southwest winds by April. In the north and central areas, southwest winds dominate. In the south, southeast winds prevail. Speeds are 5-10 knots on average with a few places, more exposed to the prevailing winds, get 15-20 knots. Sandheads and Bhubaneswar both get them. Gopalpur and Vishakhapatnam get them in the central areas, and Madurai and Madras get them in the south. Maximum wind speeds outside of typhoons approach 30 knots. See Figure 3-13 for representative wind roses.

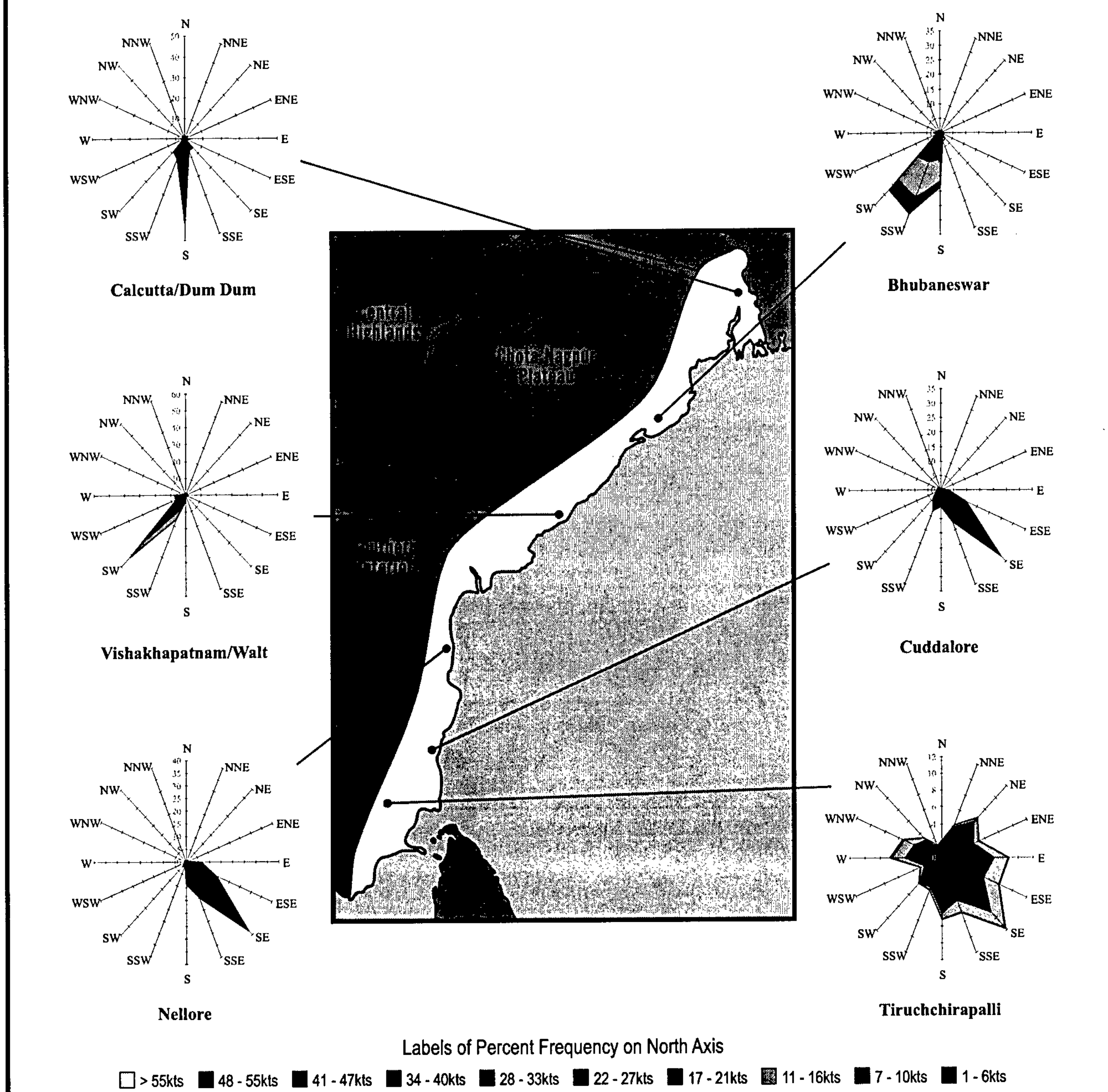


Figure 3-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. In March, 850-mb winds are northwesterly at 10-15 knots in the north and northeasterly at 5-10 knots in the rest of the region. In April and May, the winds in the north remain northwesterly at 10 knots. The rest of the region has variable winds that begin to blow mainly from the west at 5 knots by May. At 700 mb, March west winds at 25 knots shift to northwest winds in the north area at 15-20 knots by April. In the rest of the region, winds vary from northeast to southeast at 5-10 knots all season. At 500 mb, west to northwest winds at 35-40 knots prevail in the north while westerly winds blow at 5-10 knots in the rest of the region. At 300 mb, west winds at 65-70 knots blow in the north all season, but west winds at 15-25 knots prevail in the central and southern areas. Figure 3-14 shows upper-level winds for Calcutta.

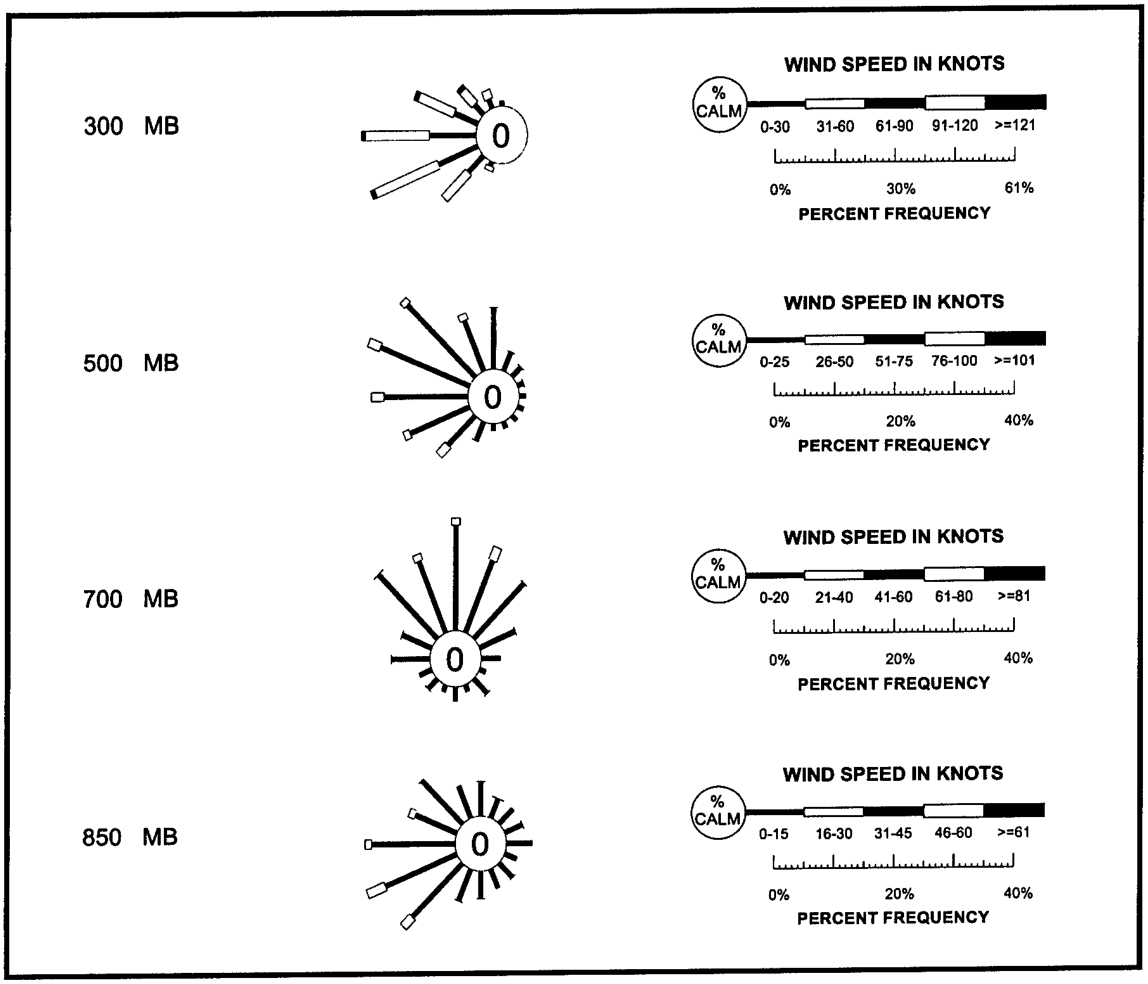


Figure 3-14. April Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Calcutta.

Precipitation. In March and April, rain amounts are 0.5-1 inch (13-25 mm), but May has a slight increase to 1-2 inches (25-51 mm) as the winds begin to bring maritime tropical air into the area. Rain falls 1-2 days in March and April and 2-4 days in May throughout the region. The southern sites get slightly more rain than the northern ones. Thunderstorm activity rises in this season. The northernmost areas get more than the rest of the region, 3-6 days per month in March and April, then 12-14 days in May. In the central areas, thunderstorms occur 2-4 days per month in March and April and up to 6 days in May. In the southern areas, the fewest thunderstorms occur, even in May. In March and April, they occur 1-3 days per month. In May, they occur 2-5 days, with the most on the southernmost tip of the peninsula. The northernmost and southernmost areas see monsoonal rains at the same time. See Figures 3-15 and 3-16 for precipitation amounts and thunderstorm and rain days.

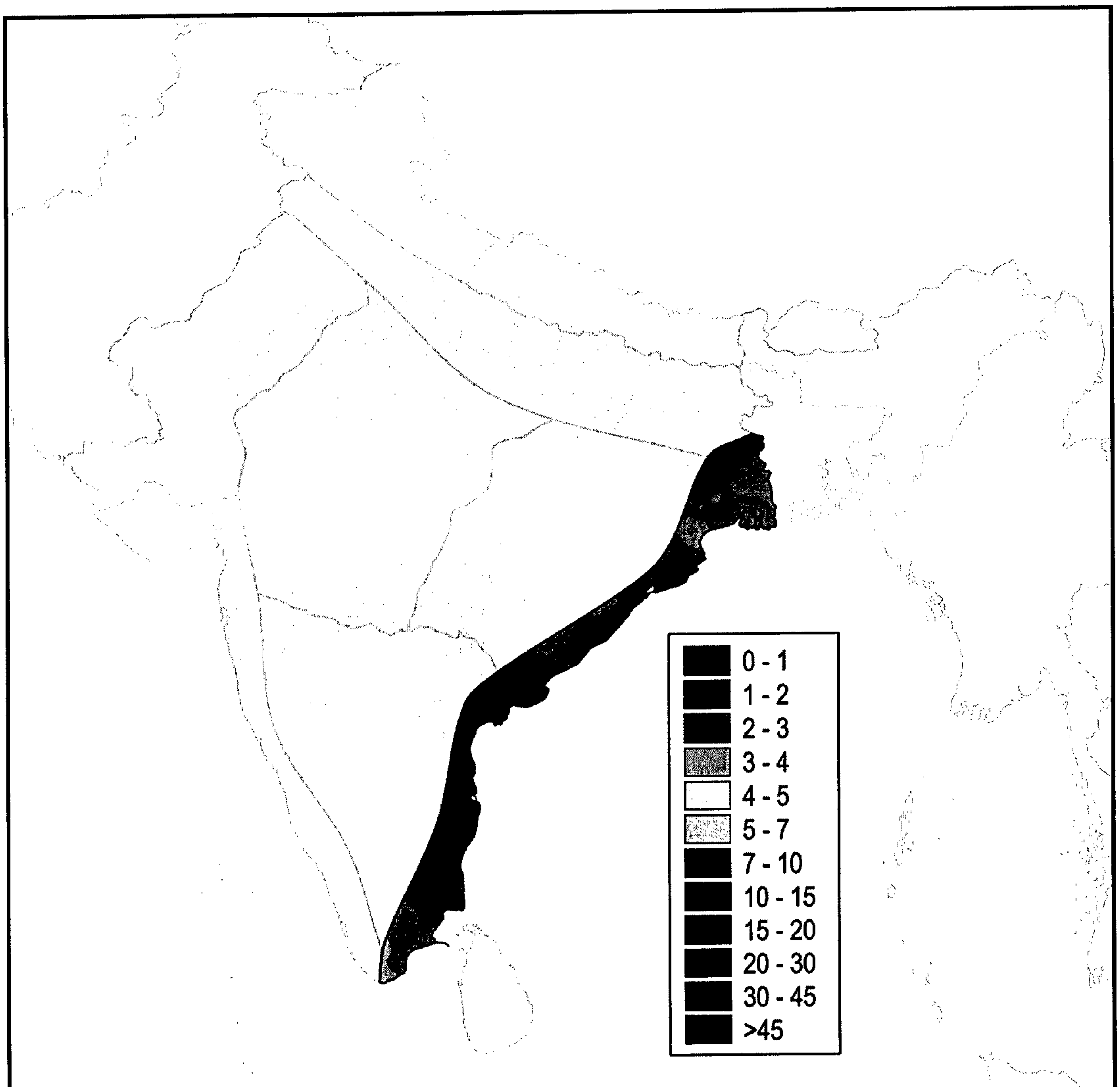


Figure 3-15. April Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

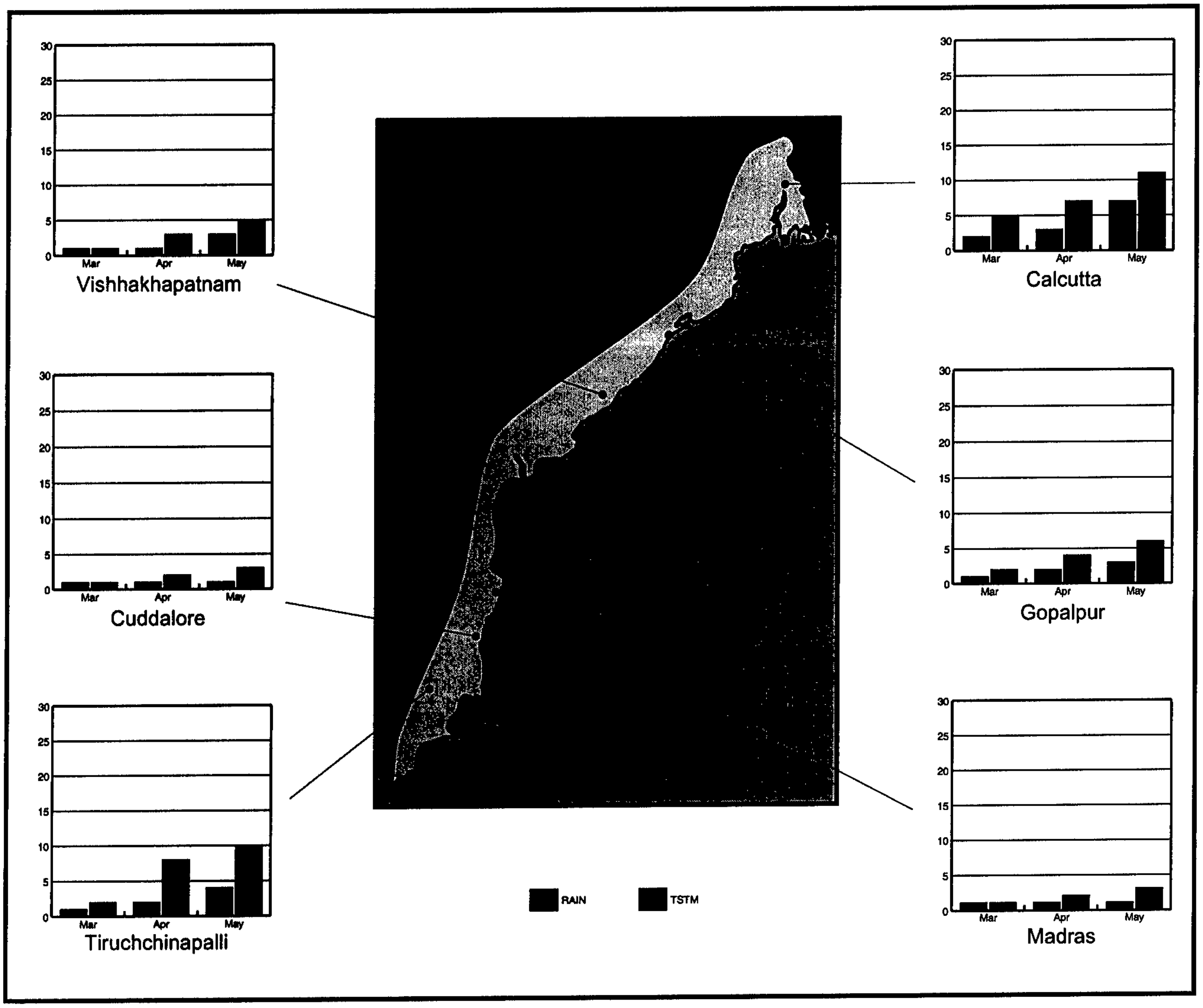


Figure 3-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. All through this area, April mean highs range from 90° to 95°F (32° to 36°C) on the coast and exceed 100°F (38°C) not far inland. Mean lows are 78° to 82°F (26° to 28°C) In May, the heat is even more oppressive, especially in the south, as humidity begins to rise. Mean high and low temperatures are as much as 5 Fahrenheit (3 Celsius) degrees hotter in May than in April and roughly 5 Fahrenheit (3 Celsius) degrees cooler in March than in April. Extreme highs are 110° to 118°F (44° to 48°C) and extreme lows are 55° to 70°F (13° to 21°C). The coldest extreme lows occur in the northern half of the region, and the warmest in the southern third. Figure 3-17 and 3-18 show the mean high and low temperatures for April.

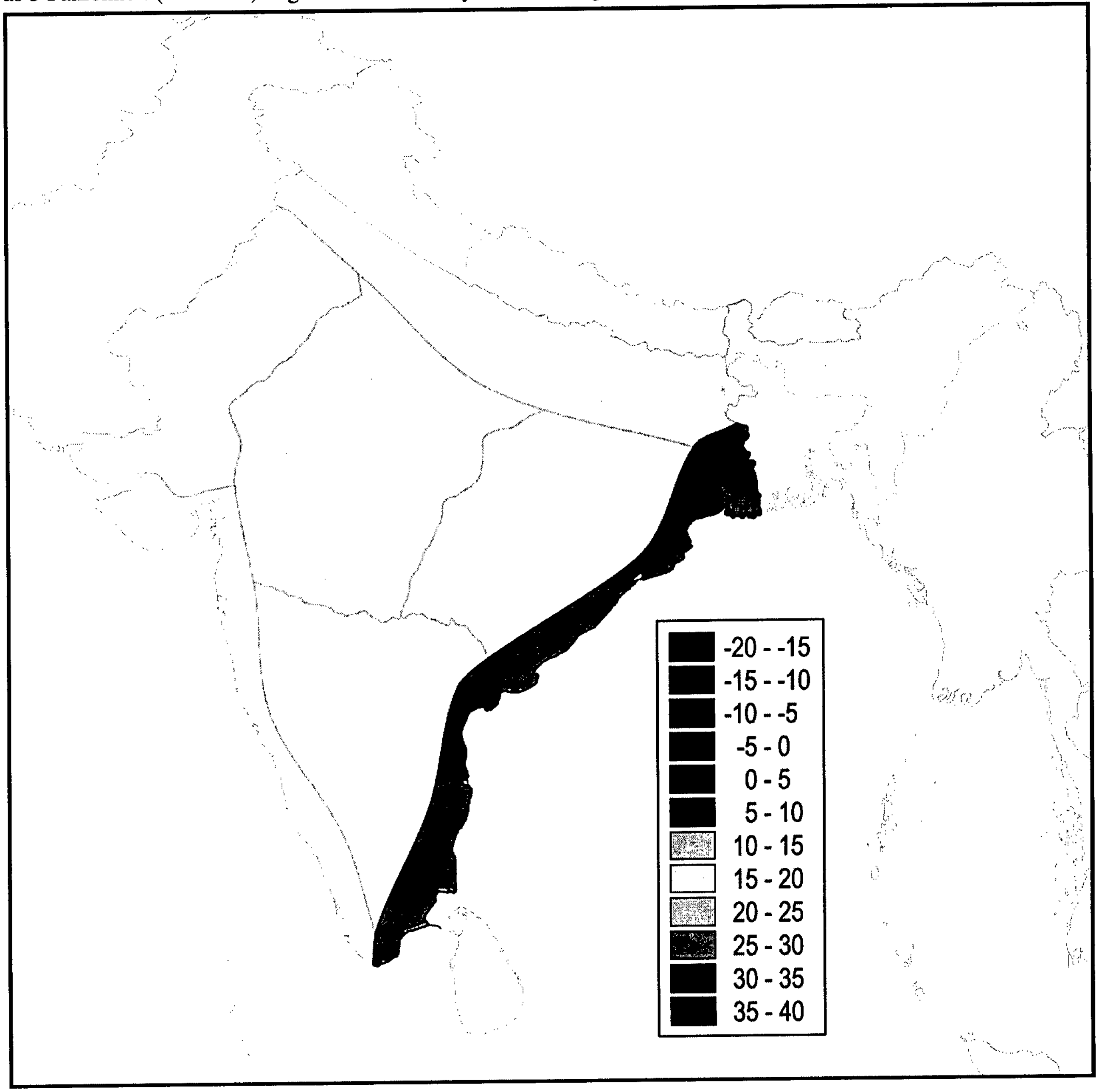


Figure 3-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

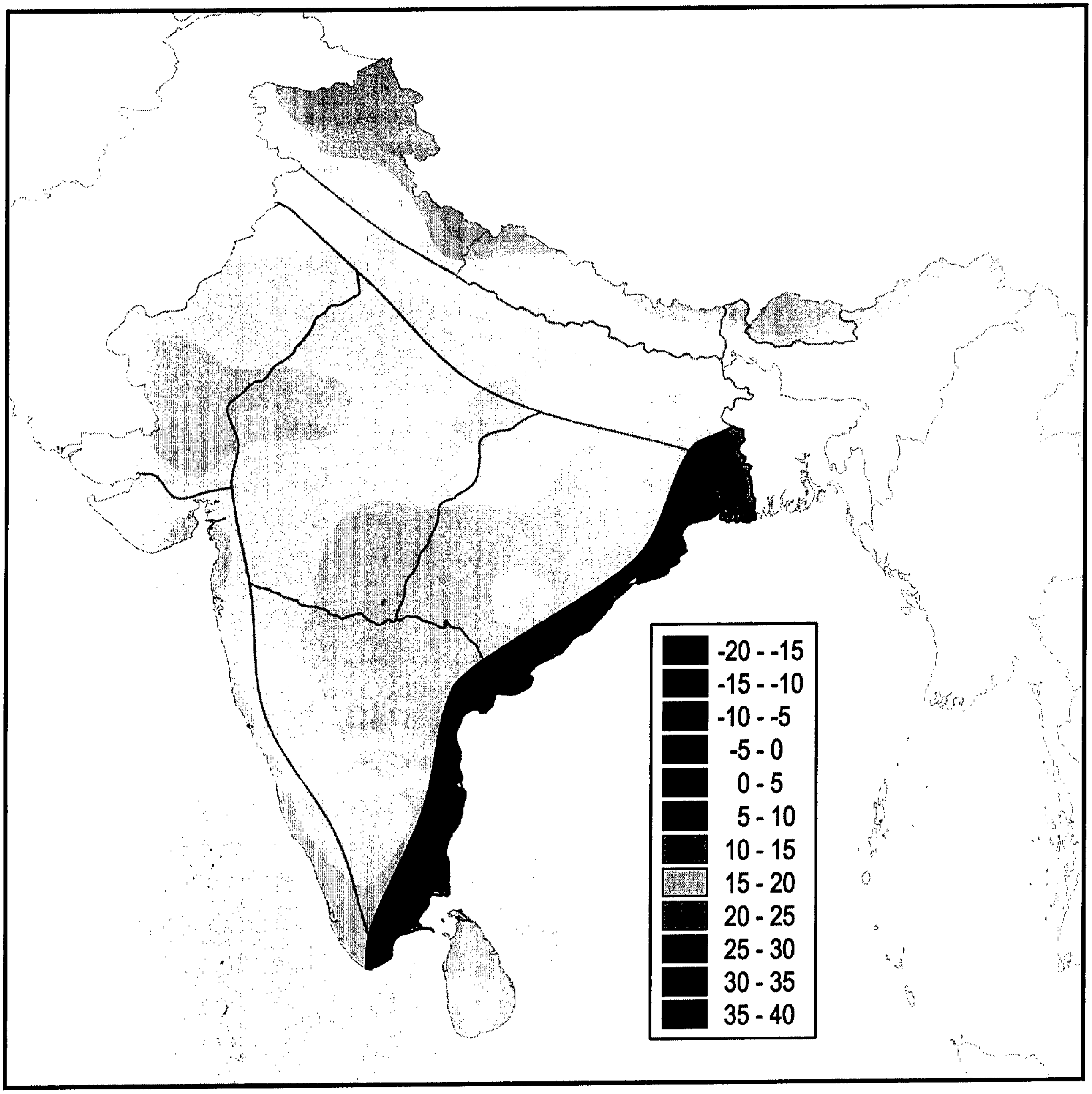


Figure 3-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. The equatorial trough (ET) moves into the area along with overall southwest flow. Although generally thought to begin in June, the monsoon actually begins as early as mid May on the southern tip of the peninsula and in the northern areas. The rest of the region gets the southwest monsoon in stages from south to north. By the end of June, the whole region is under southwest monsoon flow. By July and August, the ET is as far north as it gets, and easterly flow aloft is almost to the foot of the Himalayas. The India-Myanmar trough sets up in this season. This southwest-northeast oriented trough develops over the Bay of Bengal and is a prime breeding ground for monsoon depressions. Easterly waves and other tropical disturbances are enhanced when they make their way into this convergence zone and sometimes develop into full-blown tropical cyclones.

Mean tropical cyclone tracks are generally in the northern Bay of Bengal. In June and July, most storms tend to make landfall around Balasore (between Bhubaneswar and Calcutta) in the northeastern corner of the bay. In August through October, the tracks shift south slightly, back to the Bhubaneswar area for landfall.

The equatorial westerlies are a hallmark of the southwest monsoon season. Created by deflected outflow of the South Indian Ocean high, these low-level winds spread out over the north Indian Ocean. At the same time these winds begin to flow, the Somali jet develops. This low-level jet transports Southern Hemispheric air across the equator. This warm, moisture-laden air is what makes the southwest monsoon season rainy. The tropical easterly jet (TEJ), which is a southwest monsoon feature, provides an upper-level exhaust for Bay of Bengal convection. The bay is a prime zone for the development of tropical cyclones, monsoon depressions, and other cyclonic storms. Fortunately, storms in the Bay of Bengal are so confined in the enclosed bay, they do not become as powerful as open ocean storms. They can still carry high winds, heavy surf, and vast amounts of precipitation to the coasts. Most of the precipitation in Bay of Bengal coastal areas occurs in the southwest monsoon season.

The deep, wide band of upper-air easterlies overlay the equatorial westerlies. During this season, the easterlies are strongest and spread farthest north, almost to the foot of the Himalayas. Easterly waves ride this powerful current of air and trigger off the development of monsoon depressions and tropical cyclones. By the end of the season, the band of easterlies retreats southward toward the equator.

Thermal lows set up over the central Indian subcontinent and over the Tibetan Plateau. The Indian low becomes part of the greater Asiatic low and trough that extends from northwestern India to the Sahara. This is a source region for migratory lows that move across the subcontinent and into the Bay of Bengal. Over-lying the Tibetan low is the Tibetan anticyclone, which develops in the zone between the strong, deep westerlies of the Northern Hemispheric midlatitudes and the strong, deep easterlies of the low latitudes. The stronger the thermal low, the stronger the anticyclone. The southern edge of this anticyclone is a prime area for the development of monsoon depressions and other cyclonic storms, especially in the Bay of Bengal. The cyclonic storms that develop in the Bay of Bengal provide the rains for this region, as general southwest monsoon flow is offshore (equatorial westerlies) and carries little moisture to the area.

Sky Cover. Cloudy conditions dominate under the maritime tropical air of the southwest monsoon. Clear days are rare by the end of June and remain so through the whole season. In the south and central areas, broken-to-overcast conditions persist well past the end of the season. Average cover is broken to overcast throughout the region.

See Figure 3-19 for occurrences of ceilings below 5,000 feet. In the north, ceilings below 5,000 feet occur 20-30 percent of the time most of the day and 50-60 percent of the time in the late morning to mid-afternoon. Some places in the south are under the lee of mountains or are parallel to wind flow so the lower cloud cover is less there than most places. Madras, for example, has ceilings below 5,000 feet well under 10 percent of the time most of the day and 15-25 percent of the time in the afternoon at the height of the rainy season. Most of their ceilings are above that level as the mountains to the west shear off the low-level moisture before it gets to them. The central coast and less protected places in the south get ceilings below 5000 feet 25-35 percent of the time in June and September and 45-50 percent of the time in July and August. The central peninsular coast has more lower cloud cover. Ceilings below 1,000 feet occur rarely throughout the region even at the height of the rainy season.

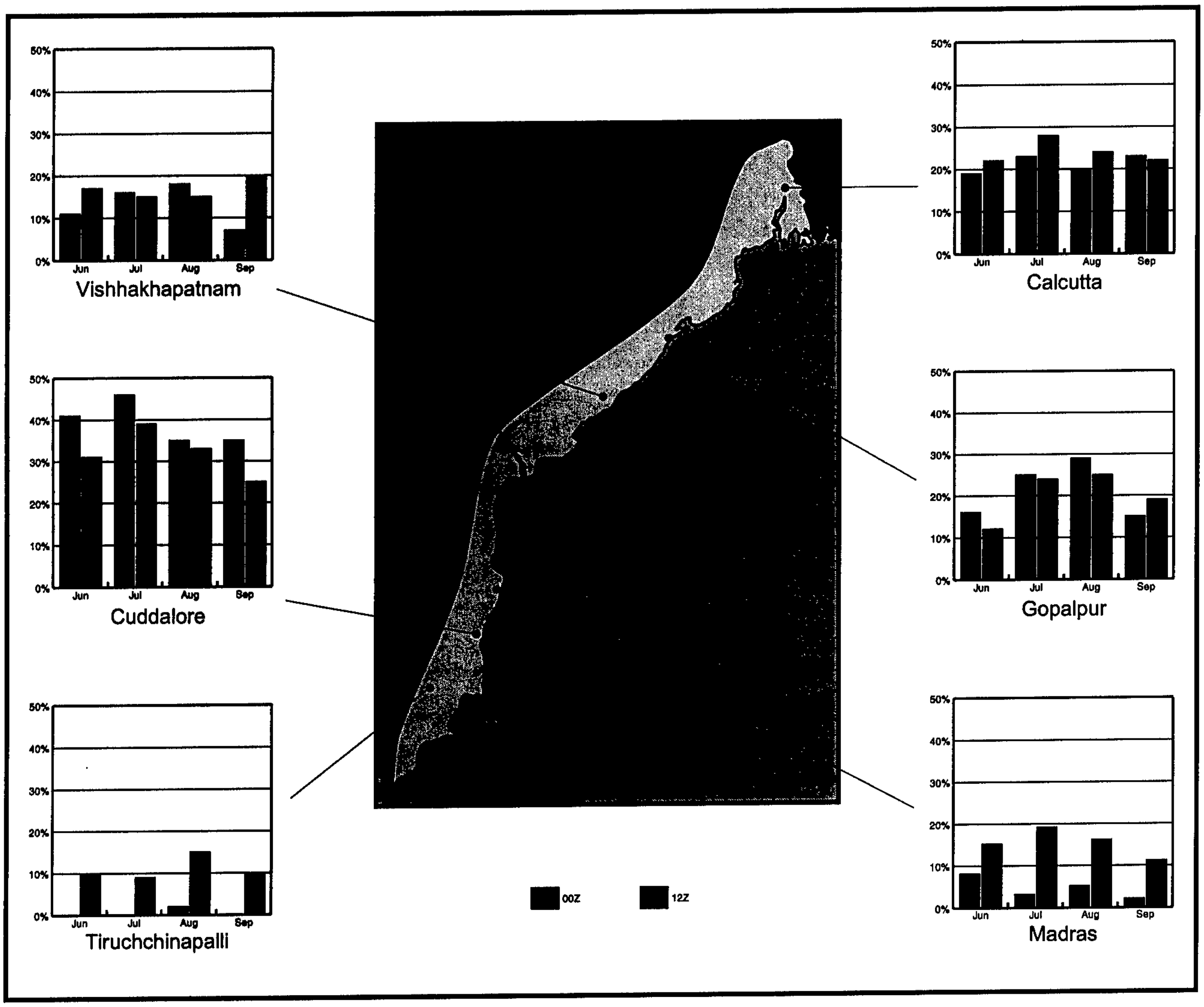


Figure 3-19. Southwest Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Any haze remaining from the hot season is washed from the air. Visibility remains good except during heavy rains when visibility may fall below 2 1/2 miles (4,000 meters). Visibility below 1 1/4 miles (2,000 meters) occurs in heavy downpours associated with localized thunderstorms or tropical depressions. Typhoons can restrict visibility to below 1 mile (1,600 meters) for hours in very heavy rain.

Visibility below 6 miles (10 km) is common with wet haze. Typically, it occurs 90-100 percent of the time in the mornings and improves by mid morning to 40-50 percent of the time. In the central and northern areas, visibility continues hazy the rest of the day. In the south, visibility remains below 10 km meters 20 percent of the time or less. Places under parallel flow see it under 5 percent of the time in the afternoon. Visibility below 4,000 meters occurs less than 10 percent of the time everywhere at any time of the day (see Figure 3-20). Visibility below 2,000 meters rarely occurs.

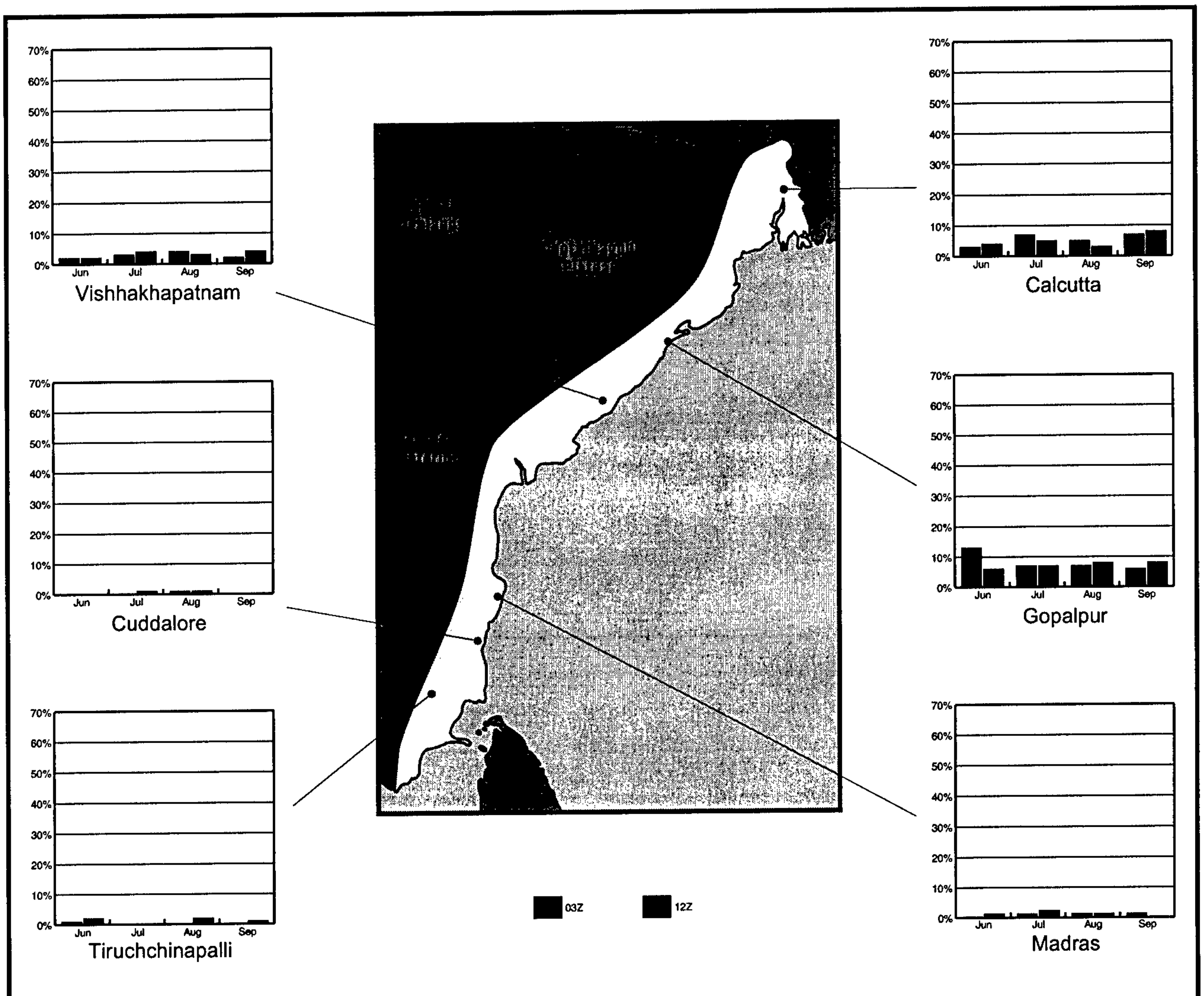


Figure 3-20. Southwest Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Southwest monsoonal flow dominates with variations in direction caused by terrain steering close to the mountains. On the coast, land/sea breezes are weaker than during the hot season, are often overridden, but still occur. Southwest flow builds in June, is at peak strength in July and August, and begins to weaken in September. A more westerly component in the wind starts in July. In the north, south or southwest winds at 10-15 knots prevail in most places. Calcutta has an average of only 5 knots, but Sandheads, out in the bay, has speeds of 12-22 knots. In the central areas, west to southwest winds at 10-15 knots prevail. Gopalpur has west-southwest winds at 10-15 knots. In the south, westerly winds with a slight southwesterly component dominate. Speeds are highest farthest south, 12-18 knots, but average 5-10 elsewhere. Tiruchchinapalli has west winds at 12-22 knots and Cuddalore has southwest winds at 5-10 knots. See Figure 3-21 for representative wind roses.

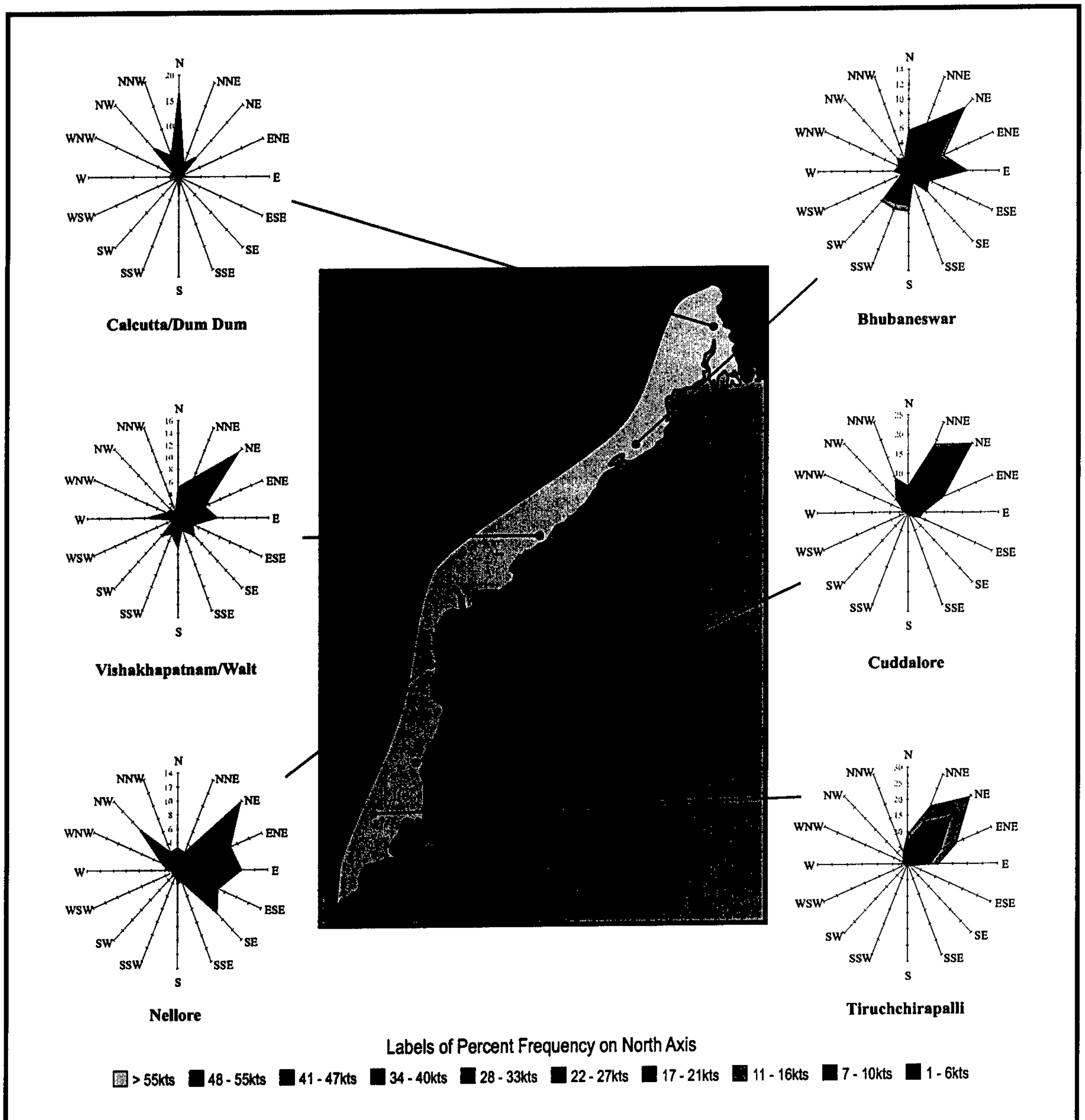


Figure 3-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Winds at 850 mb are variable at 5-10 knots in the north and range from southeast to southwest winds. The rest of the region has west winds at 20 knots. The June 700-mb winds are from the northwest at 10 knots in the north. The 700-mb winds are from the west at 15-20 knots in the rest of the region for the whole season. By July, the winds in the north come from the southeast-southwest at 10 knots and remain from that direction the rest of the season. At 500 mb, the winds in the north start the season variable at 5-10 knots and eventually settle to southeast-southwest winds by August. The rest of the region has variable winds that come out of the west at 10 knots all season. In the north, the 300-mb winds come from the southeast-southwest at 10-15 knots in June and July then shift to east at 15-20 knots in August then to south at 10 knots in September. In the rest of the region, they remain from out of the east at 10-15 knots all season. August wind speeds rise to 20 knots from the same direction. Figure 3-22 shows the upper-level winds at Calcutta.

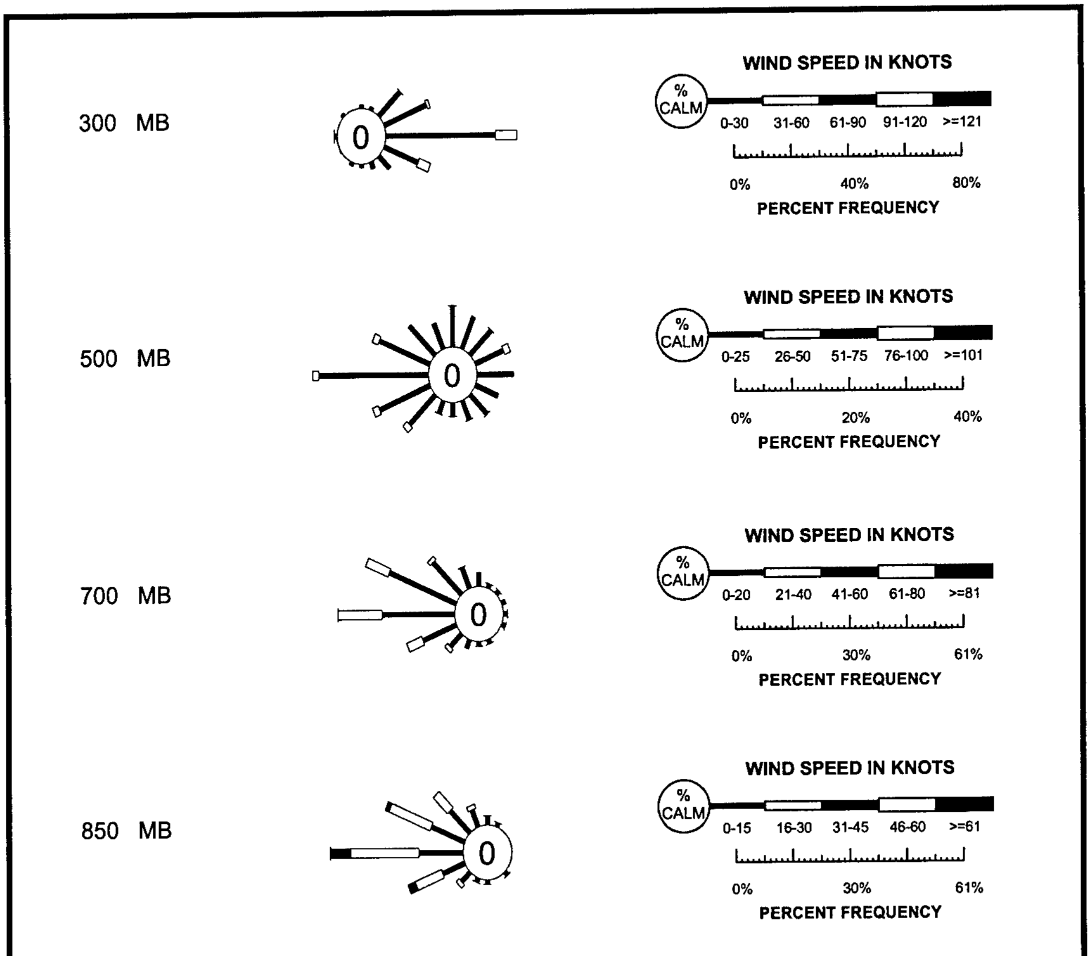


Figure 3-22. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Calcutta.

Precipitation. "Onset bursts" or "onset vortices" announce the arrival of the southwest monsoon on the southern tip of the peninsula in late May or early June. These bursts are downpours with violent thunderstorms. By mid-June, the entire coast is under southwest monsoon flow. Rain falls in pulses. Tropical depressions and monsoon depressions, which track in from the Bay of Bengal along the ET or the India-Myanmar trough, bring most of the rain. See Figures 3-23 and 3-24 for precipitation amounts and thunderstorms and rain days.

The east coast has moderate amounts of rain that increase steadily from June to September. Most places get 3-6 inches (76-152 mm) of rain between June and August and 4-7 inches (102-176 mm) in September. In the lower Ganges basin, onshore flow from the Bay of Bengal influences rainfall. Rainfall amounts there total 11-18 inches (279-457 mm) per month, with the rainiest period in July and August. Amounts taper off in September to 8-15 inches (203-381 mm) and drop sharply when the ET moves south of the area in late September or early October.

Rain falls the most days in the northern section of the region. Calcutta averages 13 days with rain in June and September and 18 days in July and August. In the lower

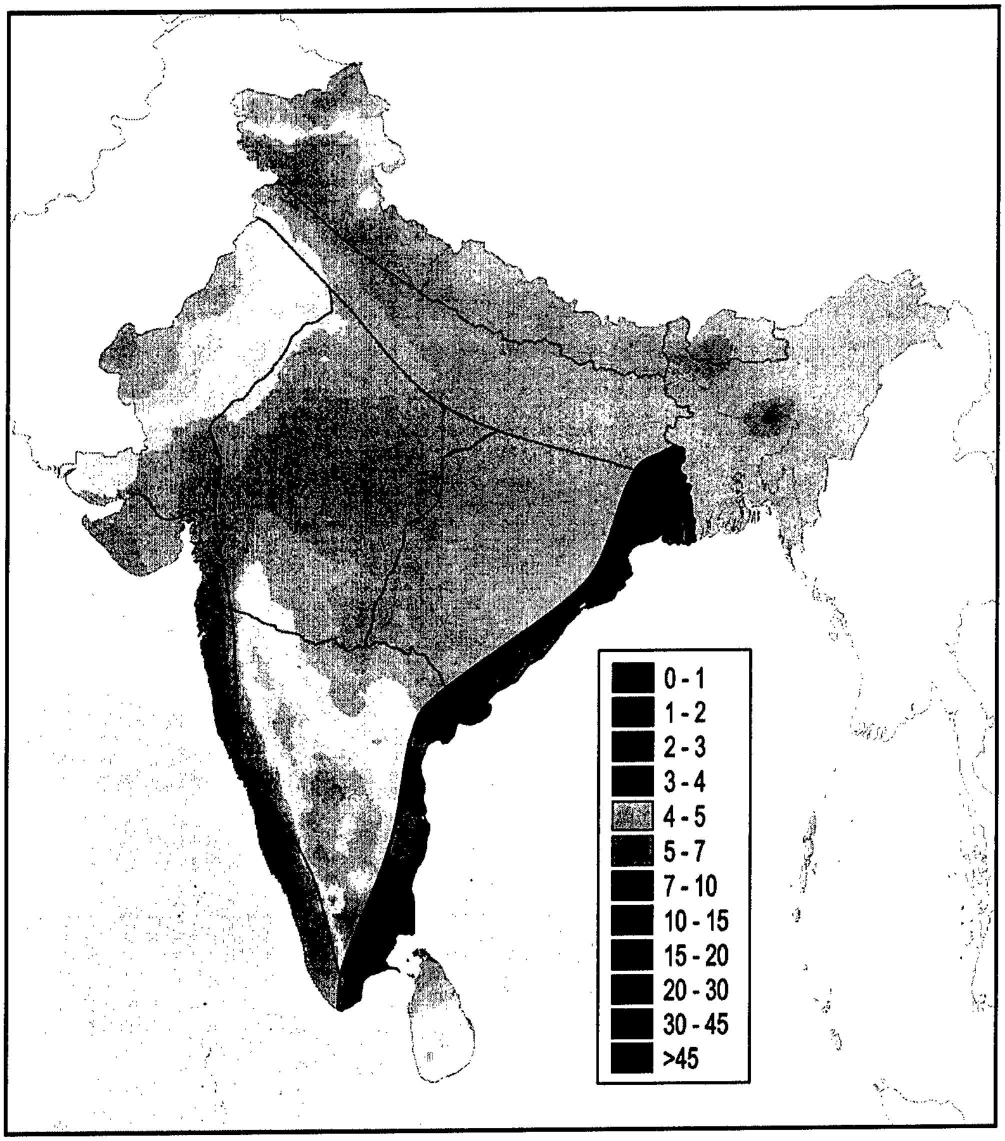


Figure 3-23. July Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

Ganges River basin, 15-20 rain days per month occur with the most days in July and August. In the central areas, rain falls 10-15 days per month with a few places in the north central coastal area getting as many as 20 days. In the south, rain falls 6-11 per month, most in July and August.

Thunderstorms are common in the lower Ganges basin. They occur 12-17 days per month. In central areas, they occur 5-7 days per month, and in the south, they occur only 2-5 days per month.areas, rain falls 10-15 days per month with a few places in the north central coastal area getting as many as 20 days. Thunderstorm activity is greatest around the equatorial trough (ET).

Rainfall varies widely from one year to the next andfrom place to place. The ET varies in strength and position and monsoon breaks occur more in some years than others. El Niño weakens the ET and the TEJ (known to intensify or trigger tropical disturbances/monsoon depressions) and creates an environment that allows breaks to occur more often than normal. In El Niño years, drought is a problem. There is also a huge variation in rainfall caused by topography and strength/orientation of the monsoonal flow. Much of the coast is roughly parallel to the wind flow in the Bay of Bengal, which limits the amount of rain caused by orographic lifting.

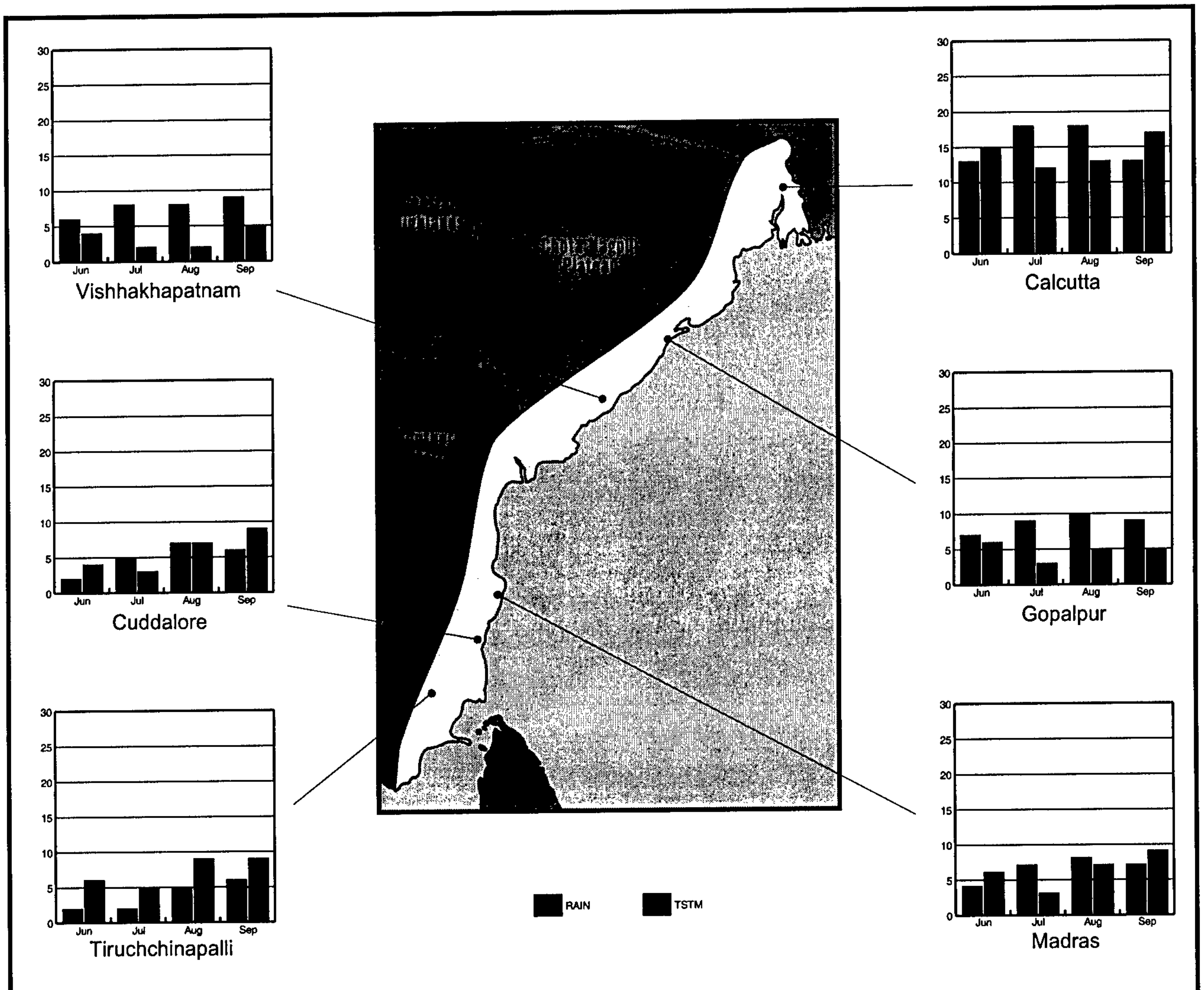


Figure 3-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Cloudy days cool the temperatures but raise the humidity; the result is oppressive heat. Temperatures cool between June and July then remain steady through September. In July through September, mean highs range from 89° to 97°F (31° to 36°C) and mean lows are 77° to 80°F (25° to 27°C). June is 3-5 Fahrenheit (1.5 to 3 Celsius) degrees hotter with the highest temperatures in the early days of the month. The extreme temperatures are moderated by the high moisture content of the air. The extreme high in June is typically higher than the other southwest monsoon months and exceeds 110°F (43°C) in most places. Cocanada reported 117°F (47°C) in June, 107°F (42°C) in July, and 99° to 100°F (38°C) in August and September. Once the rains set in, extreme high temperatures average 95° to 103°F (35° to 39°C). The coolest temperatures occur in the north and the hottest in the south. Calcutta recorded an extreme high of 113°F (45°C) in June and 98°F (37°C) the rest of the season. Extreme lows average 65° to 70°F (18° to 21°C) in the north and 68° to 72°F (20° to 22°C) in the south. Figure 3-24 and 3-25 show the mean maximum and mean minimum temperatures for July.

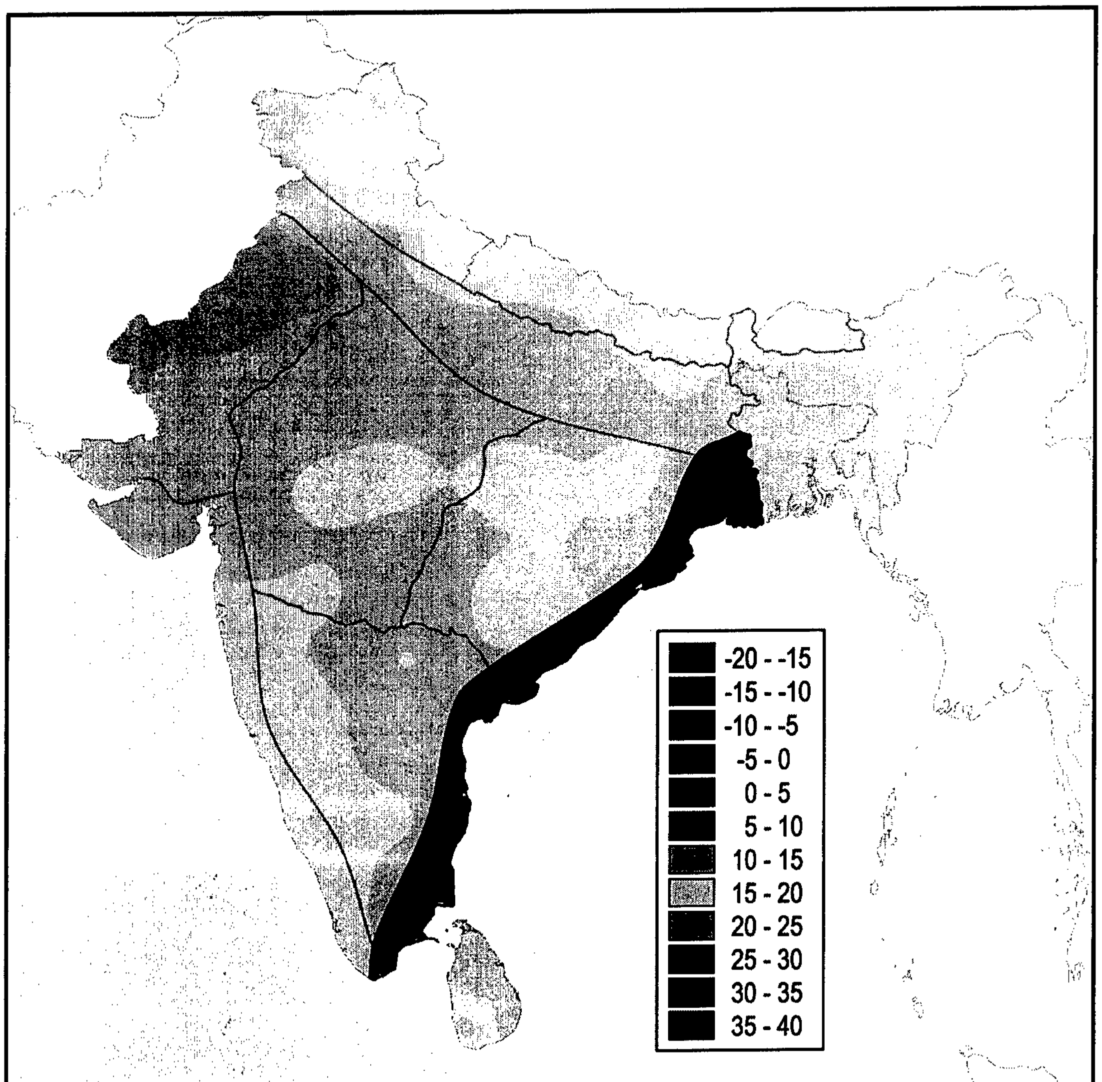


Figure 3-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other southwest monsoon months may be lower, especially at the beginning and ending of the season.

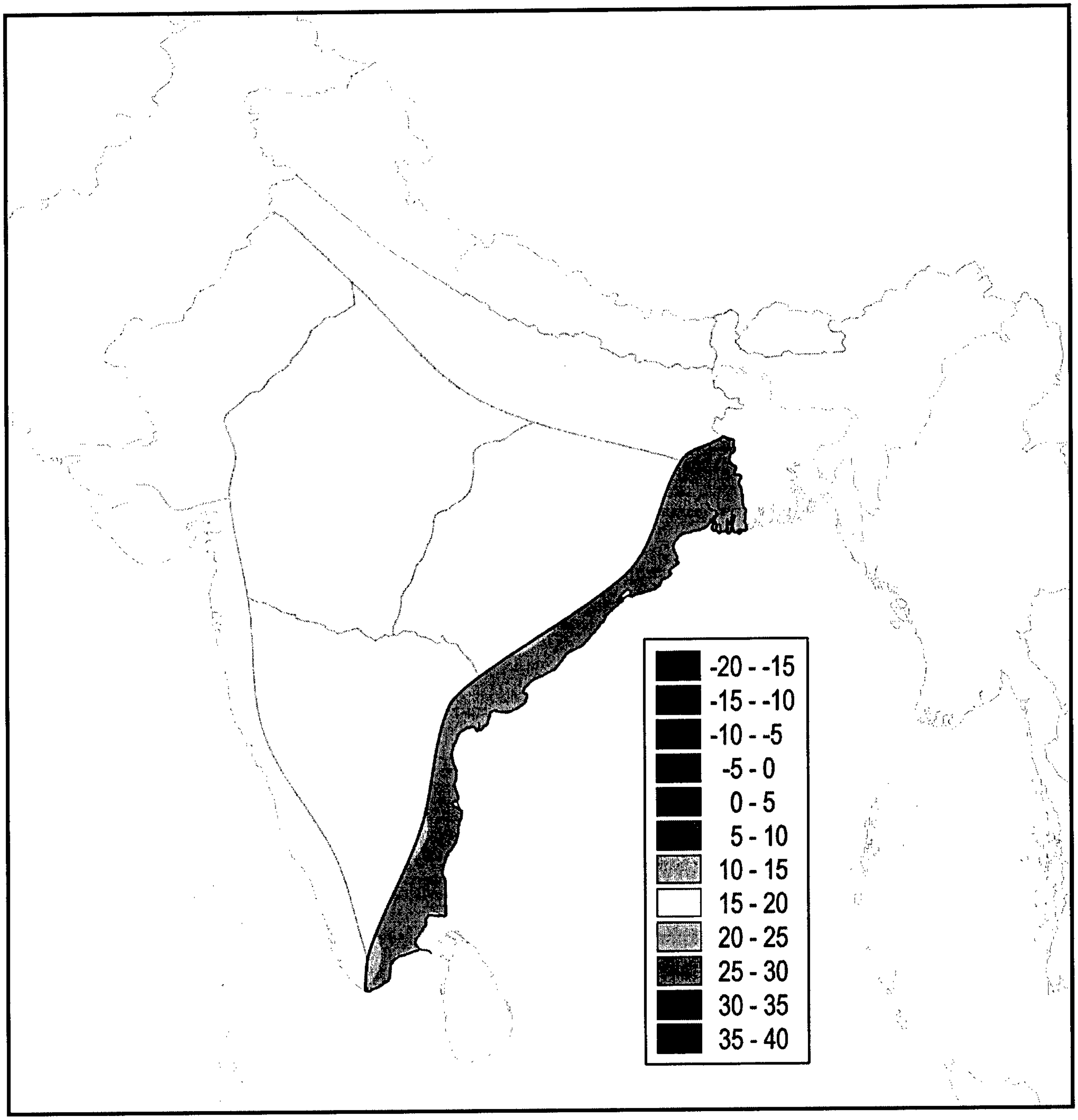


Figure 3-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other southwest monsoon months may be lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. The rains of the southwest monsoon season end. The equatorial trough (ET) begins its retreat southward as the thermal low over Asia fades away. The withdrawal of the southwest monsoon occurs more smoothly than the onset. The progression southward is usually orderly. It occurs first in the northernmost part of the region; the ET is out of northern India by mid-October. It is south of the tip of the peninsula by late November or early December. Heavy rains accompany the ET as it moves through an area.

The equatorial westerlies, the Somali jet, and the tropical easterly jet, all key elements of the southwest monsoon season, disappear. The deep band of easterlies also retreats southward in this phase. By the end of November, it will be largely south of the peninsula. The thermal high of the Asiatic winter begins to form, and wind flow at all levels is relatively ambiguous as a result. Shear aloft is reduced in this transition season, thus tropical cyclones have the best chance of developing and growing powerful. The Bay of Bengal is a favored breeding ground for tropical cyclones.

October and November are consistently more active tropical cyclone months than April and May. This is when Bay of Bengal water is warmest and storms reach maximum occurrence rates. These storms are not as powerful as open ocean storms, but they still carry heavy rains and strong winds to the coasts. The mean storm track in this season is spilt. One branch directs storms to a landfall in the northeastern coastal area around Bhubaneswar. The other directs them to the southern end of the peninsula to coastal areas just north of Sri Lanka.

By the end of November, the ET is south of India and headed for south of the equator. General, northeasterly flow is established by the end of November, and the induced leeside trough at the southern foot of the Himalayas starts to develop. This provides a track for migratory lows out of Europe. Once the subtropical jet is established south of the mountains, lows will move through very quickly. Early season lows are not uncommon by mid-November. As northeast flow becomes established, onshore winds bring winter rains to the southeast coast of the peninsula as early as the end of November.

Sky Cover. Skies clear in the north first and then progressively southward behind the ET. In the north, clear skies occur on average 15 days in October and 23-27 days in November. In the central areas, they are clear 4-8 days in October and 15-20 in November. In the south, they are clear 4-6 days in October and 12-16 days in November. Southern areas have fewer clear days as the ET lingers near the tip of the peninsula. Pamban is typical of this; it averages 6 days with clear skies in October and 3 in November. Broken-to-overcast skies occur 15-20 percent of the time in October in the north and decrease to under 5 percent of the time in November. In the central areas, broken-to-overcast skies occur 10-15 percent of the time in October and 5 percent of the time in November. In the south, broken-to- overcast conditions occur roughly 15-20 percent of the time in both months.

Ceilings below 5,000 feet occur more in October than November everywhere (see Figure 3-27 on next page). The time of day the maximum occurs depends on proximity to water. Inland locations get an afternoon maximum and coastal locations get a morning maximum. The farther north a location, the more the occurrence rate drops. Ceilings below 5,000 feet occur 15-20 percent of the time in October in the northern through central areas and drop to under 5 percent of the time in November. In the south, position relative to the ET makes a difference. In the far south, ceilings below 5,000 feet occur 25-30 percent of the time in both months, but a little farther north, they occur 15-25 percent of the time in October and 5-10 percent of the time in November. Ceilings below 1,000 feet rarely occur.

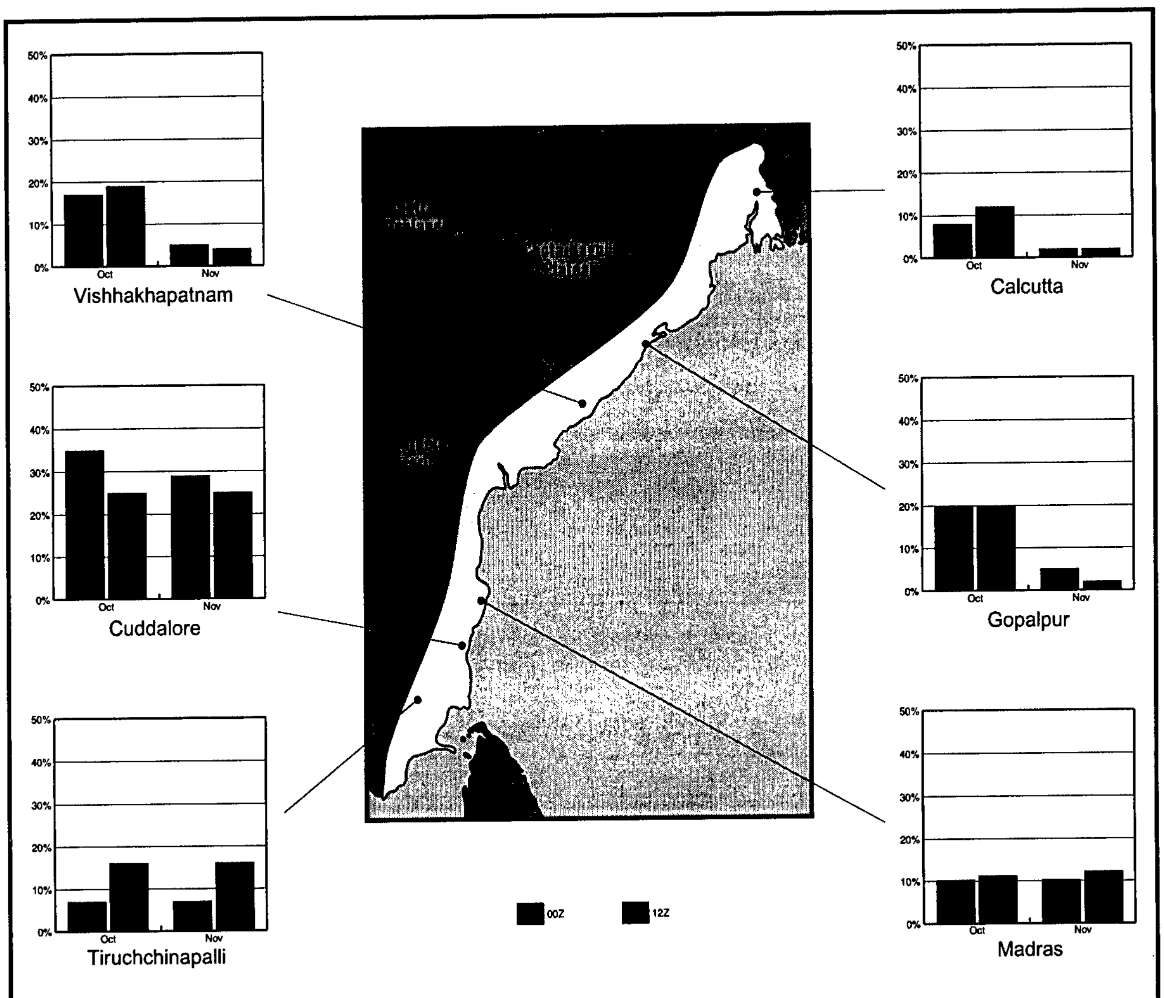


Figure 3-27. Post-Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility remains good except during heavy rain in central and southern parts of the area. Visibility in downpours associated with thunderstorms, tropical disturbances, or tropical cyclones can drop below 1 1/4 mile (2,000 meters). In the north, visibility remains fair. Visibility below 6 miles (10 km) occurs in haze 90-100 percent of the time in the mornings. Large urban centers have smog that keeps visibility below 10 km meters 75-85 percent of the time all day, but most places improve by midday to 10-20 percent of the time.

Visibility below 2 1/2 miles (4,000 meters) occurs more around sunrise than any other time of day (see Figure 3-28). Most places see it rarely, but large, urban, industrial centers, such as Calcutta, get it 10-15 percent of the time in October and 25-30 percent of the time in November. This is mostly the result of fog mixing with pollution. The largest cities suffer the most. Visibility below 2,000 meters occurs rarely at any time of day throughout the region.

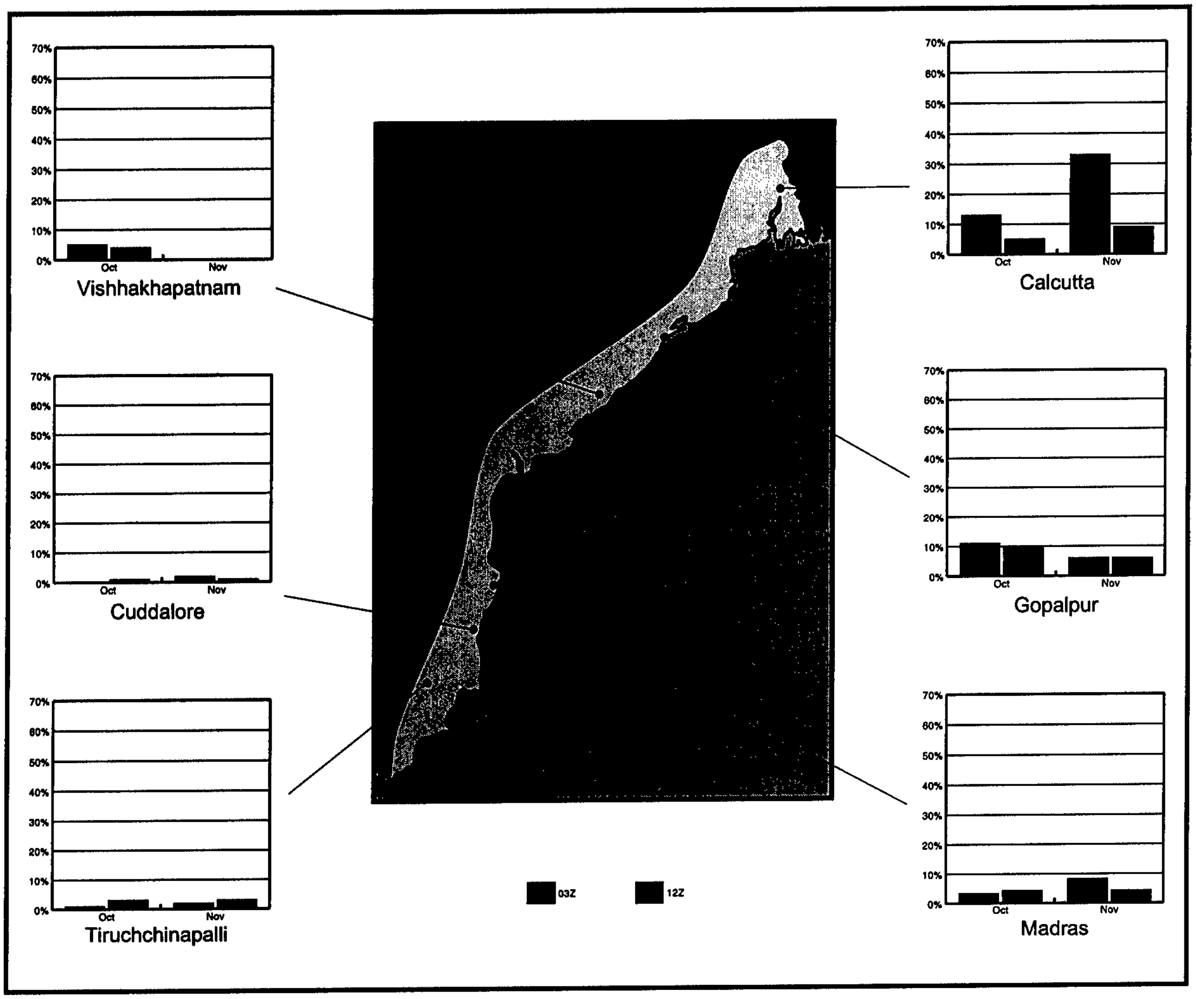


Figure 3-28. Post-Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Until the equatorial trough is south of a particular location, southwest flow remains. After passage, the winds are light and variable and gradually settle into light, northeast winds. In the north, Calcutta switches to north winds at 5 knots by October. Sandheads shows a clear transition between southwesterly and northeasterly flow. Neither direction has dominance in this site until northerly winds settle in November. Speed averages 5-10 knots. In the central areas, northeast winds at 5-10 knots dominate with some sea breeze winds in the afternoon at coastal locations. In the south, winds are variable as the ET is still close. Cuddalore averages northeast winds at 5 knots, Tiruchchinapalli still has west winds at 10-15 knots. See Figure 3-29 for representative wind roses.

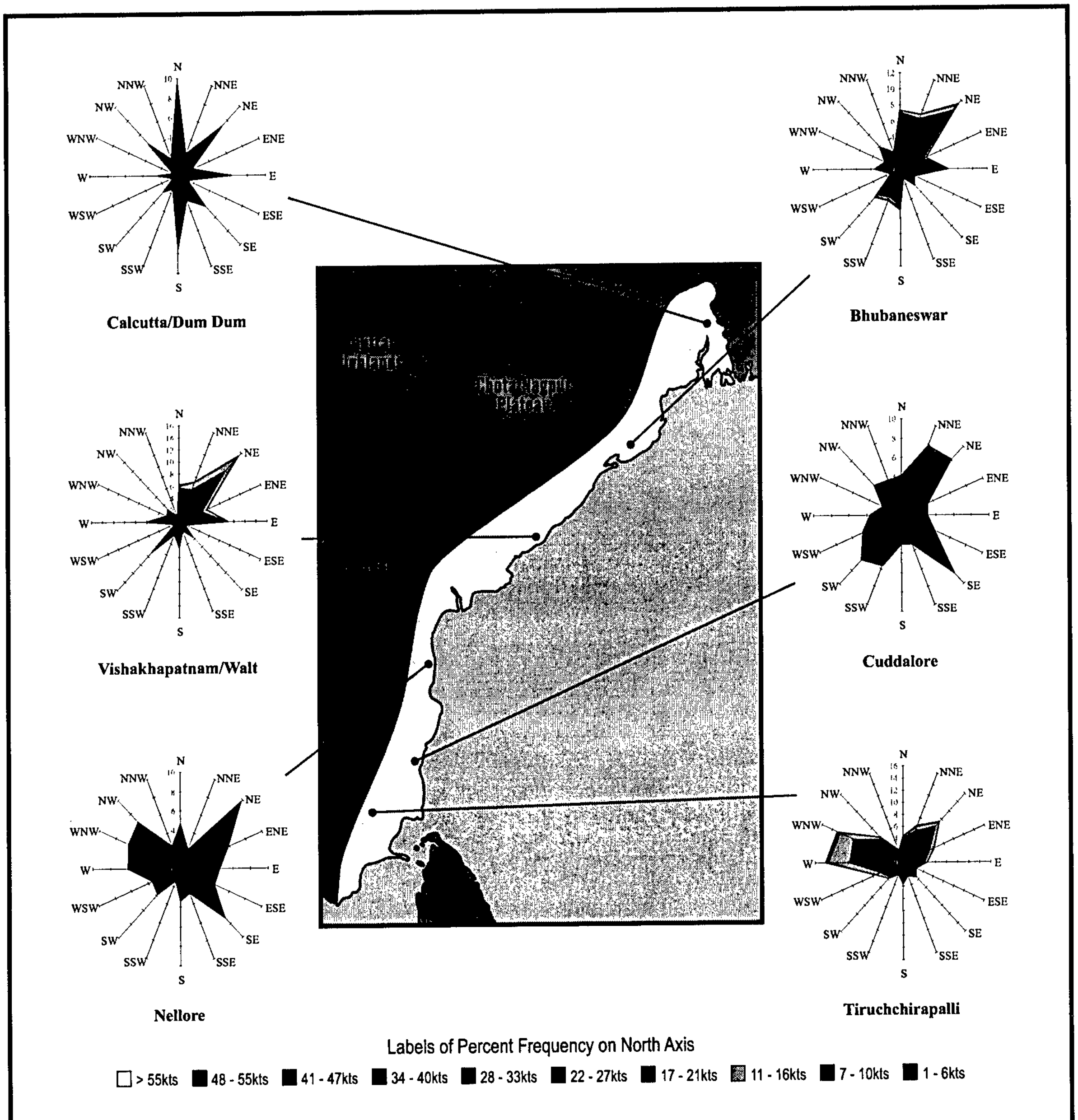


Figure 3-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The winds at 850 mb are from the northwest at 10 knots in the north in both months. In the central areas, the October 850-mb winds are from the northeast at 10 knots; the south areas have west winds at 10 knots. In November, the central and southern areas have 850-mb winds from the northeast-southeast at 10 knots. The 700-mb winds in the north hold from the northwest at 10 knots in both months. The rest of the region has easterly winds at 5-10 knots in both months. At 500 mb, the westerly winds start in the north. In October, they blow at 15 knots and by November, they rise to 30 knots. In the rest of the region, 500-mb winds are still from the east at 10-15 knots. At 300 mb in the north, westerly winds at 25 knots in October rise to 60 knots by November. In the rest of the region, easterly winds at 10 knots in October give way to southwesterly winds at 10 knots in November. Figure 3-30 shows upper-level winds for Calcutta.

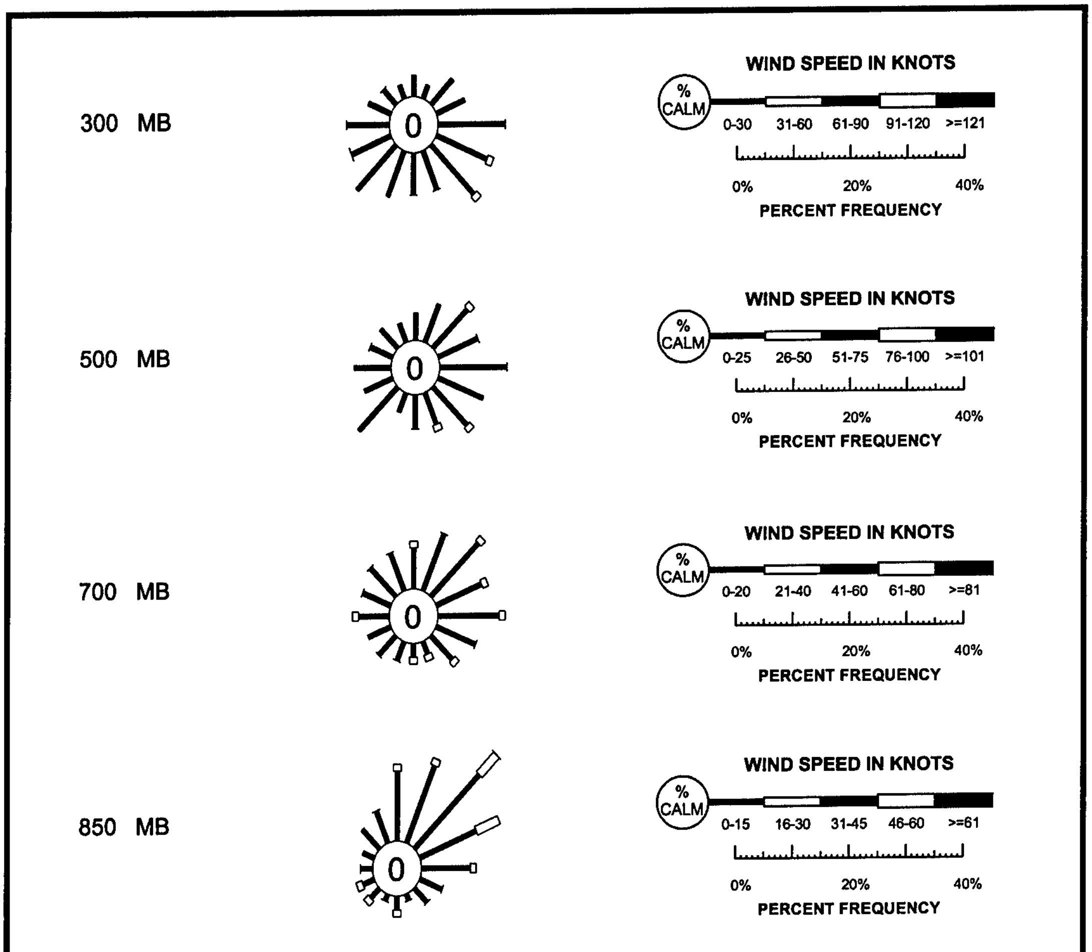


Figure 3-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Calcutta.

Precipitation. The amount of rain any area gets in this season depends upon the ET. It usually takes 2 months to move completely south of the subcontinent. As a result, the central and southern parts of this area have the most rain of the year in this season. In general, November is the rainiest month of the year for them. Rain amounts average 8-12 inches (203-305 mm) in October and 10-15 inches (254-381 mm) in November in the central and southern areas. In the north, rains drop to 5-7 inches (127-178 mm) in October and 2-4 inches (51-102 mm) in November. In both months, northern coastal sites have the most rain and inland sites have the least. At the end of November, amounts drop sharply everywhere when the ET finally moves offshore.

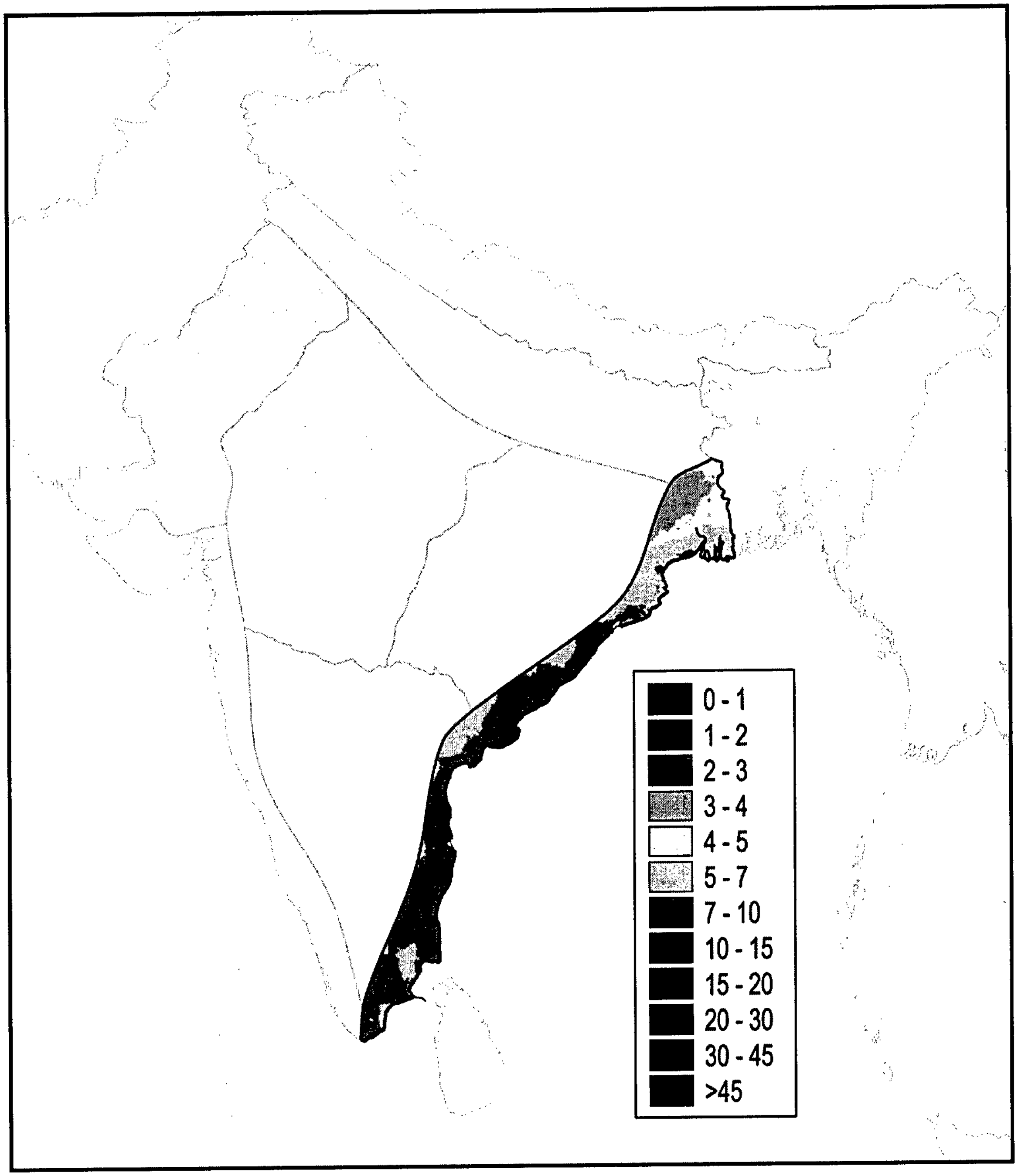


Figure 3-31. October Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

Rain falls 10-15 days in October in the north half of the region and 6-10 days in the southern half. In November, rainfall drops sharply as the ET moves off the peninsula. In the north and central areas, rain falls 2-5 days in November. In the south, rain falls 4-5 days north of Nellore and 10-12 days from Nellore south. The southernmost areas get more because the ET is still fluctuating in the vicinity. Thunderstorm activity is greatest in the southernmost areas with the ET. The north and central areas get 3-7 days with thunderstorms in October but 1 day or less in November. From Nellore south, 8-10 thunderstorms occur in October and up to 5 occur in November. See Figures 3-31 and 3-32 for precipitation amounts and thunderstorm and rain days.

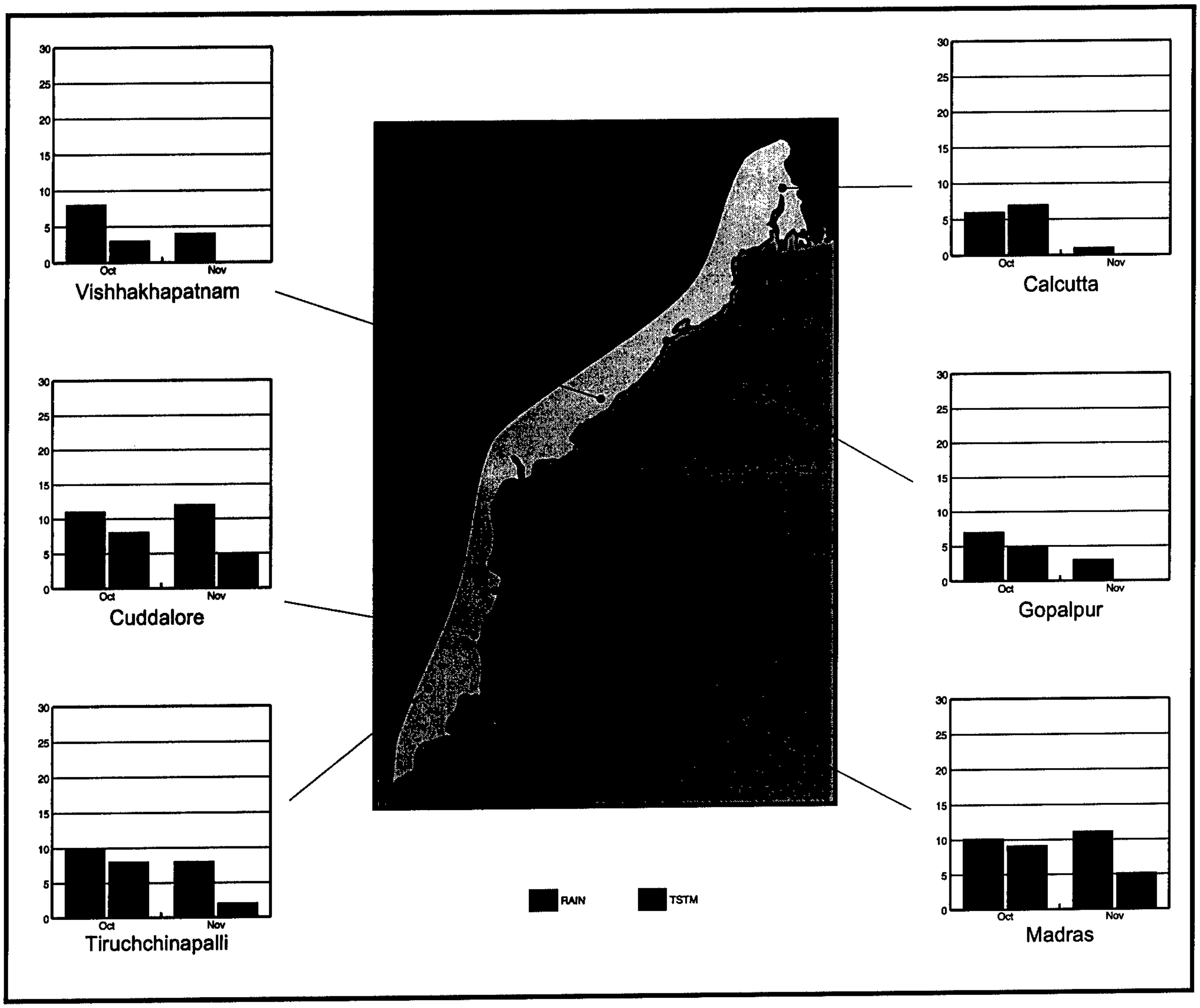


Figure 3-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Although most of India warms a bit as cloud cover clears, the south and central areas remain cloudy and relatively cooler. Temperatures cool slightly from October to November as November is the rainiest month of the year for this area. Mean highs in both months range from 88° to 92°F (31° to 33°C) and mean lows range from 73° to 77°F (23° to 25°C). In the northern parts of the area, temperatures rise from October to November as cloudiness drops behind the retreating ET. Mean highs in October range from 83° to 90°F (29° to 32°C) and mean lows range from 64° to 77°F (18° to 25°C). On average, mean highs and lows in November are 3 Fahrenheit (1.5 Celsius) degrees warmer in November. The extreme highs are 96° to 103°F (36° to 39°C) in both months. The extreme lows are 60° to 65°F (16° to 18°C) in October and 50° to 60°F (10° to 16°C) in November. Figure 3-33 and 3-34 show the mean maximum and minimum temperatures for October.

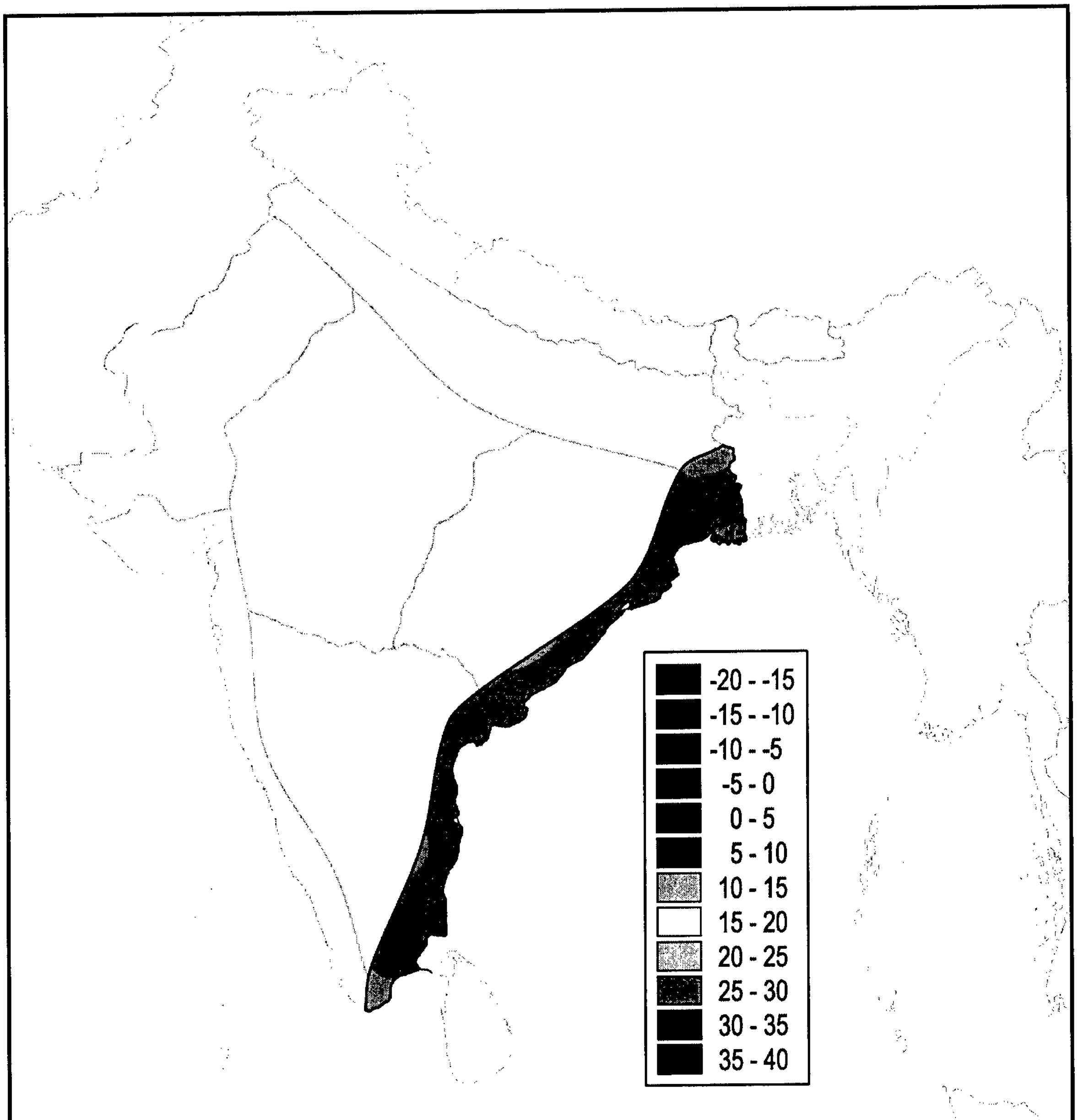


Figure 3-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in October. Daily high temperatures are often higher than the mean. Mean maximum temperatures during November may be lower.

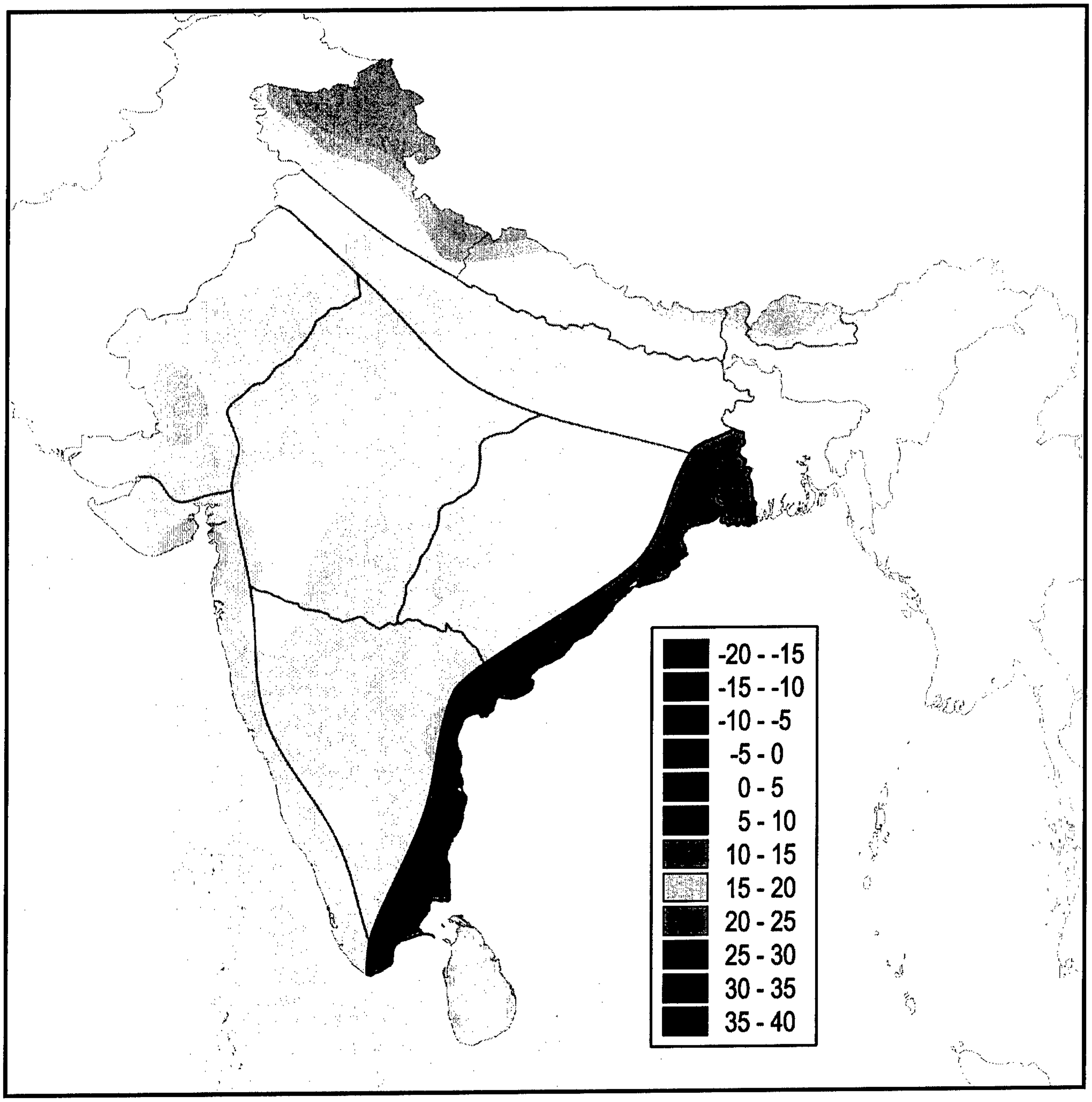


Figure 3-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in October. Daily low temperatures are often lower than the mean. Mean minimum temperatures during November may be higher or lower.

Chapter 4

SOUTHERN INTERIOR

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for the Southern Interior region of India.

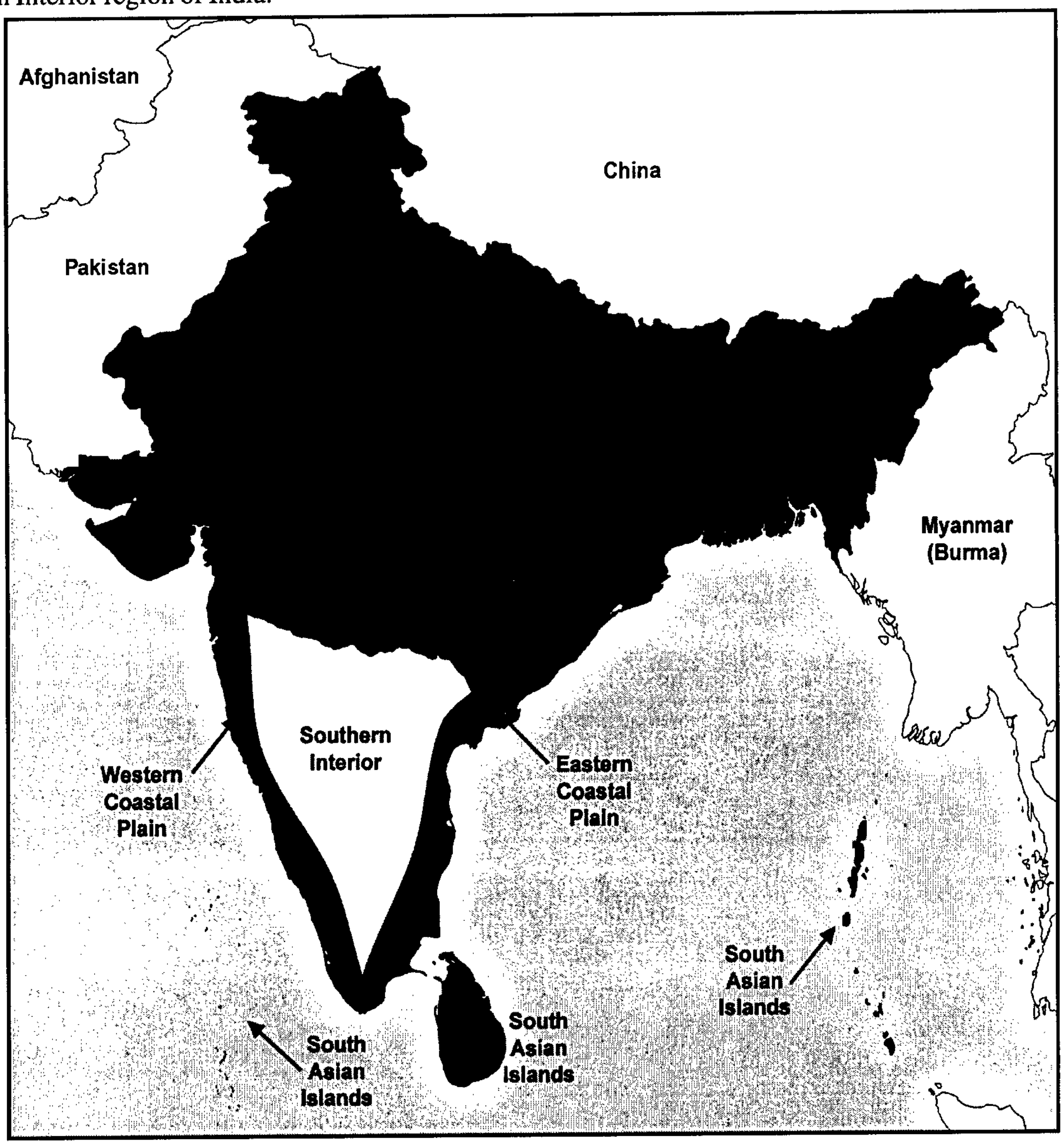


Figure 4-1. Southern Interior. The area in yellow depicts the location of this zone.

List of Topics

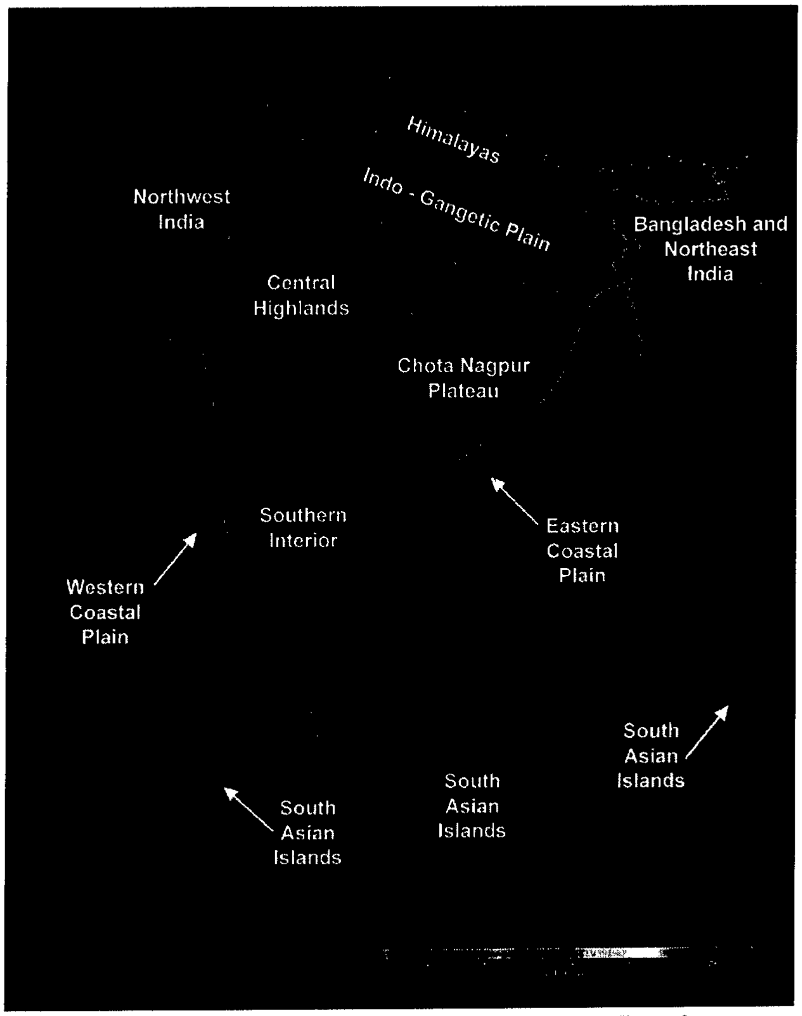


Figure 4-2a. Topographical Map of the Southern Interior.

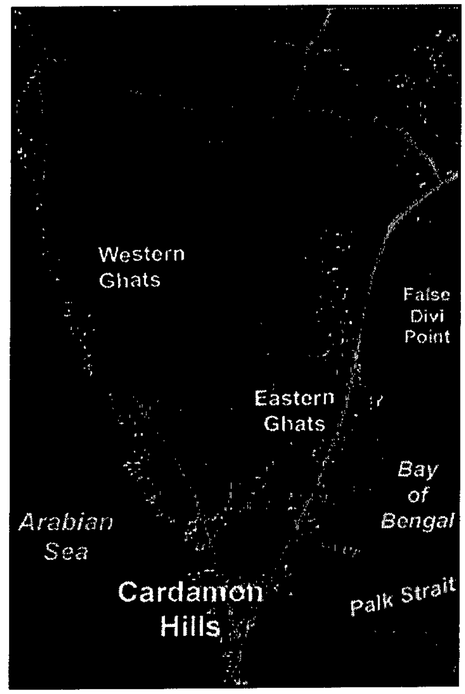


Figure 4-2b. Expanded View of Topography of the Southern Interior

Topography

Boundaries. This region, sandwiched between the two peninsular mountain ranges, includes the Deccan (also known as the Deccan Plateau) from the Godavari River (roughly 19° N) southward to the end of the Cardamom Hills, which are at the juncture of the Western and Eastern Ghats at the tip of the peninsula. The area includes the eastern slopes of the Western Ghats (to the ridge line) and the mountains of the Eastern Ghats. The coastal plains beyond them are not included.

Mountains. The Deccan is a plateau topped by a series of rolling hills and is intersected by many rivers. Most of the plateau lowland averages 1,000-2,500 feet (300-750 meters) in elevation. The Western Ghats and Cardamom Hills average 5,000-7,000 feet (1,500-2,100 meters) with many peaks above 8,500 feet (2,600 meters) south of 12° N. The Western Ghats are lower in the north half of the region. North of 13° 30' N, they average 3,000-4,000 feet (1,000-1,200 meters) with occasional peaks above 4,500 feet (1,400 meters). The ridges from the ridgeline eastward are oriented northwest-southeast. East of the Western Ghats, elevations drop quickly to the plateau lowlands. The entire area has a general west to east slope downwards toward the Eastern Ghats. South of 12° N, the Eastern Ghats rise to an average of 3,000-4,500 feet (1,000-1,400 meters) with some peaks above 5,000 feet (1,500 meters). Like the Western Ghats, they are lower in the north half of the region than in the south end, an average of 2,000-3,000 feet (600-1,000 meters) with few peaks above 3,500 feet (1,100 meters). The Eastern Ghats are discontinuous and there are many open plains areas through the range to the east coast in the northern half of the region.

Major Water Bodies. While this interior region does not abut any major water bodies, both the Arabian Sea (west) and the Bay of Bengal (east) have major effect on the weather in this region. The Indian Ocean (south) also affects the area.

Lakes. Many of the larger lakes between 16° and 20° N are man-made reservoirs in mountain river valleys of the Western Ghats. The heads of many basins between the northwest-southeast oriented ridges are filled with lakes. Hundreds of small lakes dot the Deccan plateau, some are seasonal and exist only in southwest monsoon and post-monsoon months. Numerous man-made reservoirs are liberally sprinkled over the plateau. Tungabhadra Reservoir (15° 10' N, 76° 10' E), is a large lake fed by a river of the same name. The river is dammed just west of Hospet and fills the river valley west of there for more than 25 miles (40 km). Another large reservoir is Narguna Sagar (16° 30' N, 79° 10' E), fed by the Krishna River and dammed in the southeastern corner of the lake. It fills a basin at the foot of 2,000-3,000-foot highlands and swells the Krishna River for 50 miles (80 km) upstream. Many dammed rivers are within 75-100 miles (120-160 km) of the Western Ghats foothills.

Rivers. The major rivers, from north to south, are the Godavari, the Krishna, the Penneru, the Palar, the Ponnaiyar, and the Kaveri. All rise in the Western Ghats and drain east into the Bay of Bengal. Although the Godavari River is not a large river until the Pranhita River joins it east of 80° E, it can be traced back to its beginnings on the eastern slopes of the Western Ghats (near 20° N). It marks the northern boundary of the region (more or less along 19° N) to the east coast (around 16° 30' N). The Krishna is a major river from 76° 10' E eastward. Numerous rivers flow over the Deccan plateau, many from west to east.

Major Climatic Controls

Asiatic High. This thermal high develops over Asia and dominates the weather over the entire continent from November to April. Its vast pool of cold, dry air is a key part of the northeast monsoon in south Asia. Because of the continental source of the air, the weather is dry. The leeside trough on the southern side of the Himalayas, created by flow out of this high, provides a track for storms that move out of Europe on the subtropical jet.

Australian High. This thermal high sets up over Australia during the Southern Hemispheric winter (May through October). It helps smooth the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ), which is a southwest monsoon feature. The outflow from this high also helps to push the equatorial trough (ET) northward to produce the southwest monsoon season in south Asia. This is the rainy season for south Asia.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon (November to April). This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area. This high does two different things. What it does depends on its strength and position. Although always weak, when the high is at its strongest, it tends to block low pressure systems from the track across the south foot of the Himalayas by displacing the lee-side trough that is typically in place. Obviously, the farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe that ride the subtropical jet to zip

through the region. When the Indian high is weak, it enhances western disturbances.

North Pacific High. This is a major player in the monsoon seasons of South Asia. It shifts north and west in the Northern Hemisphere summer and east and south in the winter. The high is linked to the position of the ET, which, in turn, marks the boundary between the northeast and southwest monsoons.

South Indian Ocean (Mascarene) High. This year-round high-pressure system shifts north and south with the sun. At its strongest during the Southern Hemisphere winter, this high provides cross-equatorial flow from May to October (reflected in both the Somali jet and the equatorial westerlies). This warm, moist flow contributes significantly to the ET shift to the north, which brings the southwest monsoon (and rain) to South Asia.

Asiatic Low. This is a thermal low that replaces the Asiatic high during the Northern Hemisphere summer. The land heats, and the consequent low draws in air. This contributes to the ET shift northward, which brings the southwest monsoon flow to South Asia.

Australian Low. This is a thermal low that develops over Australia during the Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the area of the Bay of Bengal and is a southwest monsoon feature (May to October). Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for the development of monsoon depressions.

Monsoon Climate. For South Asia, the monsoon climate means the subcontinent has a distinct rainy season and dry season. Under the northeast monsoon, the region is largely dry. Under the southwest monsoon, it is rainy. Onset of the rainy season varies by latitude and terrain, but it usually occurs between mid May and late June. Duration of the rainy season also varies widely. In the north, the southwest monsoon season is short; in the southern end of the peninsula, it lasts longer, often twice as long as in the far north. For more details about what constitutes a monsoon climate, read the discussion in Chapter Two.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough in this region, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north, the southwest monsoon takes over in South Asia. When it shifts south, the northeast monsoon assumes control. Chapter 2 offers more details.

Bay of Bengal. This large bay is the primary breeding ground for tropical cyclone storm systems that affect this region. Most of the rainfall in this area occurs from storms that develop or refire over this body of water along the ET, the India-Myanmar trough, or from other mechanisms. The northern half of the bay is more active than the southern half, but storms develop here year-round. The most active times are in October-November (maximum activity) and April-May (secondary maximum). Storms tend to come ashore on the east coast of the peninsula then recurve northward.

Special Climatic Controls

Tropical Easterly Jet (TEJ). This jet exists only during the southwest monsoon season. An upper-level jet that overlays the low-level westerlies, it provides an outflow mechanism for disturbances that develop below it. The heaviest precipitation in South Asia occurs directly beneath the TEJ. The Bay of Bengal and the Arabian Sea are both under the TEJ. The Bay of Bengal is well known to be a prime area for the development or regeneration of monsoon depressions, tropical cyclones, tropical waves, tropical vortices, and mesoscale convective complexes. The TEJ is an important element in the process.

Somali Jet (Low-Level Jet). Also known as the East African low-level jet, this jet exists during the southwest monsoon season and is a key transport for air from the Southern Hemisphere into the Northern Hemisphere. It

has been suggested 50 percent or more of the cross-equatorial flow from the Southern Hemisphere into the Northern Hemisphere is moved by this jet. It is created when outflow from the South Indian Ocean high flows toward the thermal low pressure over northern Africa. The western edge of the outflow airmass piles up against the eastern slopes of the high mountains of the eastern African coast. The result of this squeeze is a terrain-induced zone of tight pressure gradient and the jet develops there. The Somali jet is a key element in the development of the equatorial westerlies that dominate the southwest monsoon season.

Equatorial Westerlies. These winds exist during the southwest monsoon season. These large-scale, low-level winds are a result of a combination of factors. Outflow from the South Indian Ocean high (from the southeast) flows toward the thermal low over northern Africa (to the northwest), but the high mountains on the eastern coast of Africa are significant barriers that force a deflection. The Somali jet then helps transport the air into the Northern Hemisphere. The airmass is recurved eastward and these westerly winds take over throughout the monsoon region.

Subtropical Jet (STJ). This jet is significant in this region in the northeast monsoon season when its southern branch slips south of the Himalayas. Low-pressure systems out of Europe (western disturbances) ride the jet through the northern part of India, Bangladesh, and East India. During the southwest monsoon, the SJT is north of the Himalayas.

Western Disturbances. These develop from short waves in the larger, long-wave pattern. They move from west to east and are often most easily observed at 500 mb. In South Asia, particularly in winter, several waves move across the northern portions of the subcontinent and give rise to cloudiness and precipitation. The STJ, south of the Himalayas in winter, provides transport to rapidly move theses waves into and through the area.

Tibetan Anticyclone. This Northern Hemisphere (southwest monsoon) upper-air feature sets up in the zone between the deep easterlies that reach almost to the foot of the Himalayas by July and the deep westerlies of the Northern Hemisphere midlatitudes. Formed above the thermal low of the Tibetan plateau, it is important to the climate during this season because tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. Also, since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought. For a more detailed descriptions, review Chapter Two.

Easterlies. This deep east wind band persists year-round in the low latitudes. It shifts north and south with the sun. During the southwest monsoon, it shifts north and widens to encompass a larger area. Thanks to a number of factors, it also strengthens enough to develop the tropical easterly jet, a broad ribbon of higher winds that strongly influence the development of monsoon rains, tropical disturbances of all intensities, and monsoon depressions. During the northeast monsoon, the band of easterlies narrows and shifts south. At the height of the northeast monsoon, the easterlies are held south of 5° N.

Easterly Waves. During the southwest monsoon season, easterly waves are known to help fire the formation of monsoon depressions over the northern Bay of Bengal. They travel from east to west in the deep easterlies and last 1-2 weeks. They are accompanied by clear weather ahead of the trough and heavy showers and thunderstorms behind. They sometimes create cyclonic vortices offshore at the southwestern end of the Indian peninsula and can cause thunderstorms and rainshowers over the southern tip of the peninsula. The intensity and frequency of occurrence of easterly waves are indicators of the strength of the monsoon.

Cyclonic Storms. Monsoon depressions, tropical cyclones, tropical waves, tropical vortices, mesoscale convective complexes, and cloud clusters are all types of cyclonic storms of varying scales of intensity and size. Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Some travel into the area from the west (western disturbances). The ET influences the weather during the transition periods when it moves through the area. During the northeast monsoon, western disturbances and tropical vortices are the bigger players in the development of weather systems. Regardless of when they develop, some storms can be fierce. Because the waters of the bay are so confined, however, storms

do not have the opportunity to develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation to the shores of India and Bangladesh, cause extensive flooding and loss of life, and destroy crops and property. Storms tend to come ashore on the peninsular east coast of India then recurve northward. The heaviest precipitation falls in the southwest through south quadrants of the storms.

Monsoon Depressions/Low-Pressure Systems. These are important synoptic-scale disturbances that make major contributions to the monsoon circulation in organizing low-level convergence. During the southwest monsoon season, these storms move along the ET toward the north. They normally form in the Bay of Bengal north of 18° N and move west-northwest across India. They bring heavy rains, especially in the southwest quadrant of the storm. These systems rarely develop into tropical cyclones and are associated with a series of low-pressure systems and easterly waves in the northern Bay of Bengal. The strongest winds are in the southern sector of the storms thanks to augmentation by the equatorial westerlies. Approximately 80 percent of the total number of depressions that form in the South Asia region are monsoon depressions. The majority of monsoon depressions and other cyclonic storms form in the Bay of Bengal as opposed to the Arabian Sea and most of them form in the northern part of the bay.

Land/Sea Breeze. These winds are caused by diurnal land/sea temperature differences. By day, the sea is cooler than land and the wind blows onshore. By night, the temperature difference reverses and the winds become offshore. Onshore winds produce cloud cover and convection over land. During the southwest monsoon, sea breeze winds are augmented by the synoptic flow and reach far inland, as much as 100 miles (160 km). This brings moist air well inland to rise up mountain slopes and cause precipitation in the mountains. Offshore winds clear the skies over land by pushing cloud cover out to sea.

Hazards for All Seasons

Turbulence. In winter and the hot season, convective turbulence may reach 10,000 feet. The turbulence is usually light-moderate but can reach the severe category. Mechanical turbulence downwind of the Western Ghats may occur up to 50 miles (80 km). The turbulence is usually moderate but may reach the severe category. Obscured by the heavy clouds of the southwest monsoon, rotor clouds will not be visible. Moderate-to-severe turbulence will be encountered in the vicinity of the subtropical jet at 35,000-40,000 feet during the winter and hot seasons. During the southwest monsoon, moderate-to-severe turbulence occurs near the tropical easterly jet at 40,000-45,000 feet.

Icing. The mean height of the freezing level is 16,000-18,000 feet. The mean height of the -20° C isotherm is 26,000-28,000 feet. Above and below these levels, icing does not usually occur. During winter and the hot season, there is little threat from icing. Heavy, dense clouds blanket the area during the southwest monsoon. In clouds, icing could occur between 16,000-28,000 feet.

Thunderstorms. Thunderstorms occur most in May-June and September-October, during the ET advance and retreat. Thunderstorms may produce torrential rain, strong wind gusts, violent up and down drafts, turbulence, icing, lightning, and in-cloud hail. Hail seldom reaches the ground; if it does, it is usually small, soft, and causes little damage.

Flooding. Incredible amounts of rain fall in a very short period of time during the southwest monsoon. Streams and rivers overflow their banks and fill the valleys. Flash floods occur with little or no warning.

Temperature. Temperatures and humidity are high all year. These conditions are debilitating and often very dangerous.

Tropical Cyclones. Bay of Bengal storms occasionally move across peninsular India and bring heavy, layered clouds and torrential rains. Two tracks are common. One takes storms to landfalls in the northwestern corner of the bay. The other, the more favored of the two, takes them across the southern third of the peninsula. While coastal areas are most vulnerable to the full range of destruction a storm brings, inland areas are also subject to flooding and high winds.

Winter

General Weather. In winter, the northeast monsoon dominates. The massive thermal high over Asia is a driving force for pushing the ET south of the equator. The thermal low over Australia helps pull it southward. This is a dry season influenced by migratory low-pressure systems from Europe. These western disturbances bring cloudiness and rain to northern India. The subtropical jet shifts south of the Himalayan massif and pushes these lows along the induced leeside trough at the southern foot of the mountains. The moisture retained after the long trip from Europe is joined by a little moisture from first the Arabian Sea and then the Bay of Bengal as the lows zip through the northern section of India, Bangladesh, and East India. These migratory lows keep northern India cooler and more cloudy than would be expected for mostly offshore flow. The storm track along the foot of the Himalayas exists from December to March and is at its southernmost position at the end of the season. It vanishes entirely by late March. The deep band of easterlies that dominate upper-air flow in the southwest monsoon are held south of 5° N and do not influence the weather in this region nearly as much as the westerlies that take over in this season.

Onset of winter (northeast monsoon) occurs at different times that depends on latitude and terrain. The ET retreat southward marks the onset on the season. Obviously, winter occurs first in the north and last at the south end of the peninsula. Usually, the ET moves south of the north end of the region (Calcutta and the rest of the west Bengal basin area) by the middle of October. It does not move south of the Palk Strait/ Gulf of Mannar area, until the end of December. The northeast monsoon brings northerly winds to the north parts of this region and northeasterly winds to the southern part of the peninsula. These winds bring rain to the southeastern coast of the peninsula and spread inland to the windward slopes of the plateau.

Tropical cyclones and other cyclonic storms are less likely in this season than during the southwest monsoon; however, the storm season extends to November. The transition periods in October-November and in April-May, when the ET travels through the Bay of Bengal, are when the cyclonic storm occurrence rates peak. Although the rate drops off sharply after November, there is an incidence of at least once storm in every month of the year. The minimum number occurs in February, when the northeast monsoon is at its greatest strength.

Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Western disturbances, easterly waves, and vortices also grow into storms over the warm waters of the bay. While some of these factors have a greater influence during the southwest monsoon season, such as easterly waves and the India-Myanmar trough, the early and late parts of the northeast monsoon season still experience weather stirred by them. Regardless of when they develop, the storms can be fierce. Because the waters of the bay are so confined, however, storms do not develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation, cause extensive flooding and loss of life, and destroy crops and property. Storms in this season are most likely to strike the southern tip of the eastern peninsula.

Sky Cover. For the most part, clear-to-scattered skies dominate the area. In the south, the retreating southwest monsoon and late tropical cyclones bring more cloudiness early in the season. Winter cloudiness is typically middle or high cloud with bases above 9,000 feet. Average cover decreases from December through February from 50-60 percent to 25-30 percent. Interior areas have less cloud cover than those near the coasts. The high elevations, especially those windward to flow, have the greatest cloud cover. Diurnally, the most cover in the highlands occurs in late afternoon and least occurs overnight through sunrise. In the lowlands, the maximum is in the morning and the minimum in the afternoon through evening. See Figure 4-3 for ceilings below 5,000 feet at representative locations.

Ceilings below 5,000 feet occur most in late afternoon in the southernmost highlands in December and January. They occur 25-35 percent of the time on December and January mornings and 20-25 percent of the time on February mornings. In the afternoons, ceilings below 5,000 feet occur 50-60 percent of the time in December and January and 40-50 percent of the time in February.

Cloud cover does not dissipate quickly overnight in December or February. At midnight in those months, ceilings occur 45-55 percent of the time. There is lull in January, when midnight ceilings below 5,000 feet occur 20-30 percent of the time. In the highlands, ceilings below 5,000 feet occur 25-35 percent of the time in the mornings of December and January and 10-20 percent of the time in February. In the lowlands, ceilings below 5,000 feet occur most in the morning hours but are not common at any hour. In the mornings, they occur 3-10 percent of the time in December, well under 5 percent of the time in January, and almost never occur in February. They occur under 5 percent of the time the rest of the day; by February, they are rare.

In the lowlands, ceilings below 1,000 feet occur very rarely. They occur most in the southern highlands (Cardamom Hills) where cloud frequently cloaks the mountain slopes. In December and January, ceilings below 1,000 feet occur 20-30 percent of the time overnight and in the morning. During the late morning to early evening hours, they occur 40-50 percent of the time. The rates drop in February to 10-15 percent of the time overnight and in the mornings and 20-25 percent of the time during the mid morning to early evening hours. In the remainder of the region, highland areas have ceilings below 1,000 feet 15-20 percent of the time only in the morning in December and January. In February, they rarely occur.

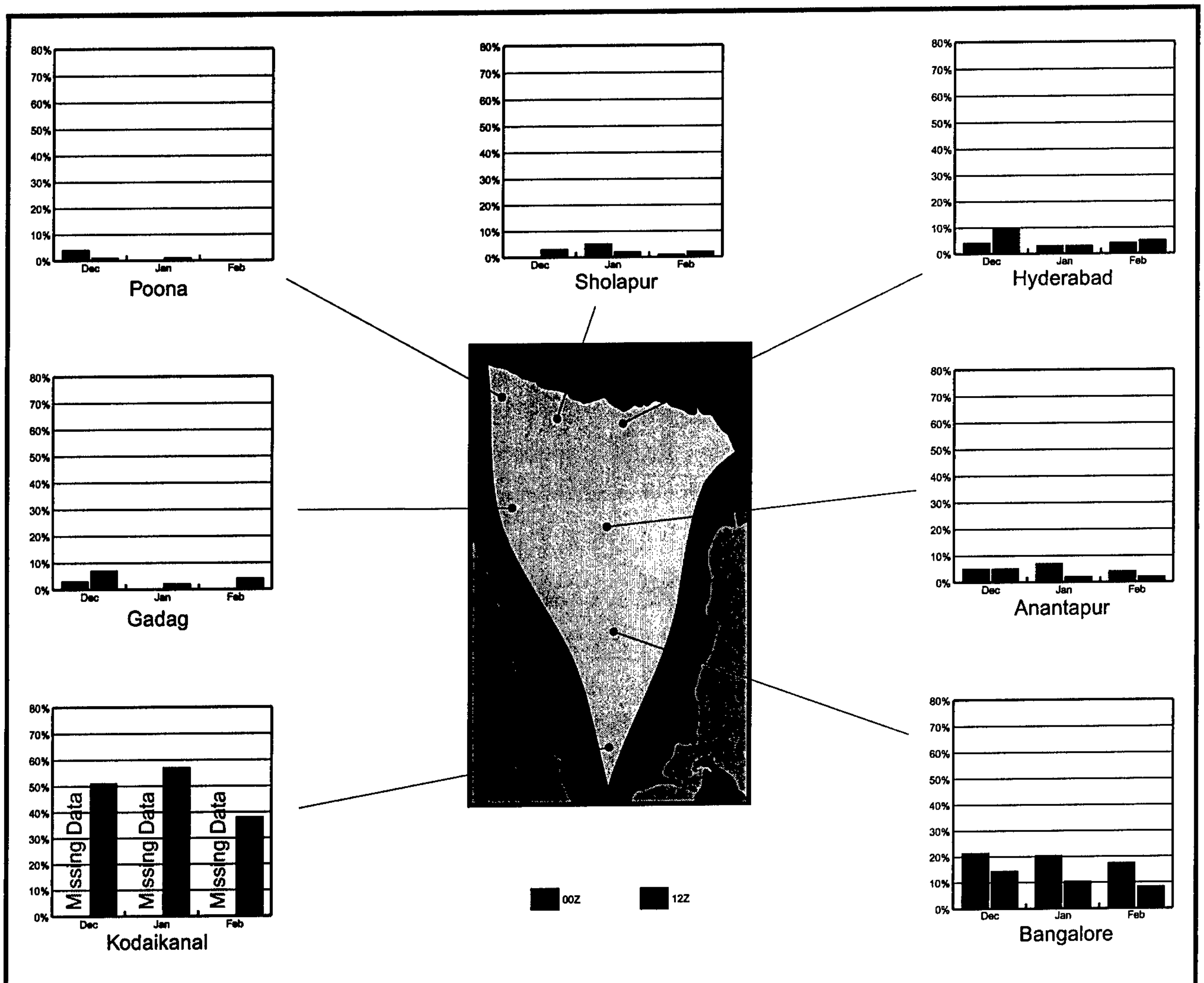


Figure 4-3. Winter Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Very low visibility is an infrequent occurrence almost everywhere. The southernmost highlands have low visibility in clouds that cloak the mountain slopes. Dust may reduce visibility in February as the soil dries and cloud cover is limited, but it does not often drop visibility outside of heavily trafficked areas. In the lowlands and the central and northern highlands (at lower elevations than those farthest south), the best visibility of the day occurs in the afternoons and reductions in fog typically occur at sunrise. In the southern highlands, the worst visibility is in the afternoons, as moisture lifts out of the lowlands. The best visibility occurs overnight. See Figure 4-4 for visibility below 2 1/2 miles (4,000 meters) for representative stations.

In the lowlands, visibility below 4,000 meters occurs well under 5 percent of the time at all hours all season. In the central and northern highlands, morning visibility below 4,000 meters occurs 25-35 percent of the time in December and January and 15-25 percent of the time in February. By afternoon, it rarely occurs all season. In the southernmost highlands, morning visibility below 4,000 meters occurs 25-35 percent of the time in December. In January, it occurs 15-25 percent of the time, and in February, it occurs 5-15 percent of the time. By afternoon, the rates increase to 40-50 percent of the time in December and January and 10-20 percent of the time in February. This drop in February reflects the period of minimum cloud cover, which is the "fog" this area experiences in cloud cloaking.

Visibility below 1 1/4 miles (2,000 meters) rarely occurs in the lowlands all season. It occurs 3-8 percent of the time all season in the central and northern highlands. It burns off 1-2 hours after sunrise and rarely occurs the rest of the day. The southernmost highlands have far more moisture available, and visibility restrictions are more common. Overnight and morning visibility below 2,000 meters occurs there 20-30 percent of the time in December, 15-20 percent of the time in January, and 5-10 percent of the time in February. Conditions deteriorate in the afternoons. Visibility is below 2,000 meters 35-45 percent of the time in December and January and 10-15 percent of the time in February.

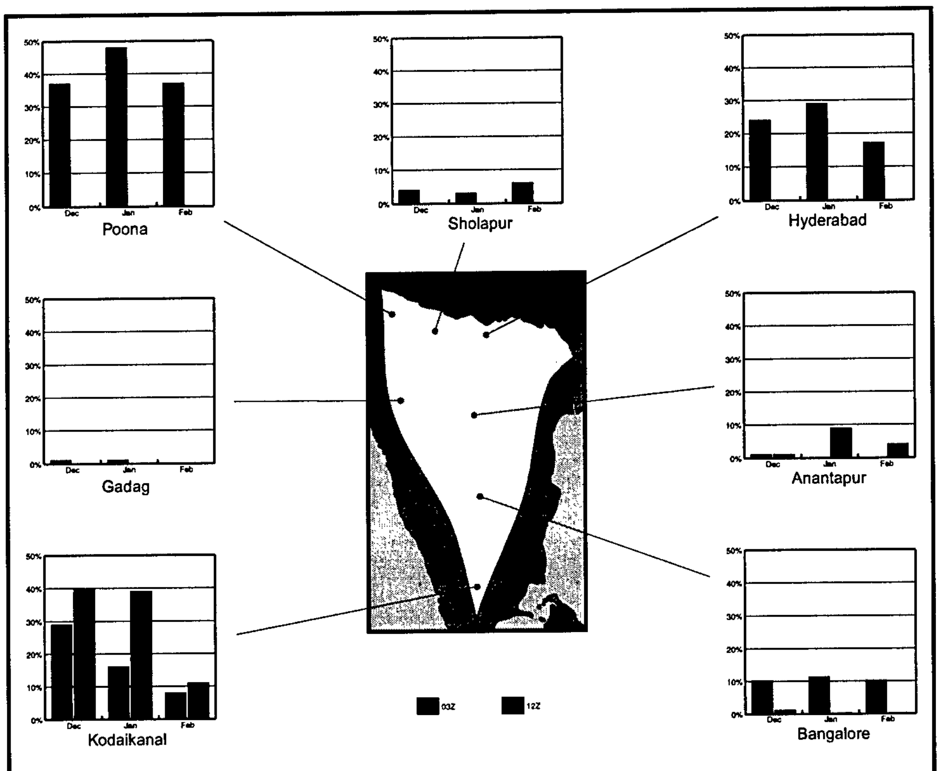


Figure 4-4. Winter Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Although terrain influences wind direction and speed, most of the region has northeast to east winds during the day and east to southeast winds at night. Speeds average 5-10 knots in the lowlands and sheltered areas and 10-15 knots at higher elevations. Calms are most common overnight in the lowlands, 70-90 percent of the time, and in the sheltered valleys of the Western Ghats, 80-95 percent of the time. At higher elevations on the Deccan plateau, overnight calms typically occur 15-25 percent of the time. Poona, in a valley of the western Ghats, has light and variable winds all day and has a high rate of calms, 96 percent of the time overnight and 32 percent of the time during the day. Bangalore, in contrast, has persistent east winds at 5-10 knots at all hours and calms occur just 9-15 percent of the time. See Figure 4-5 for surface wind roses at representative locations.

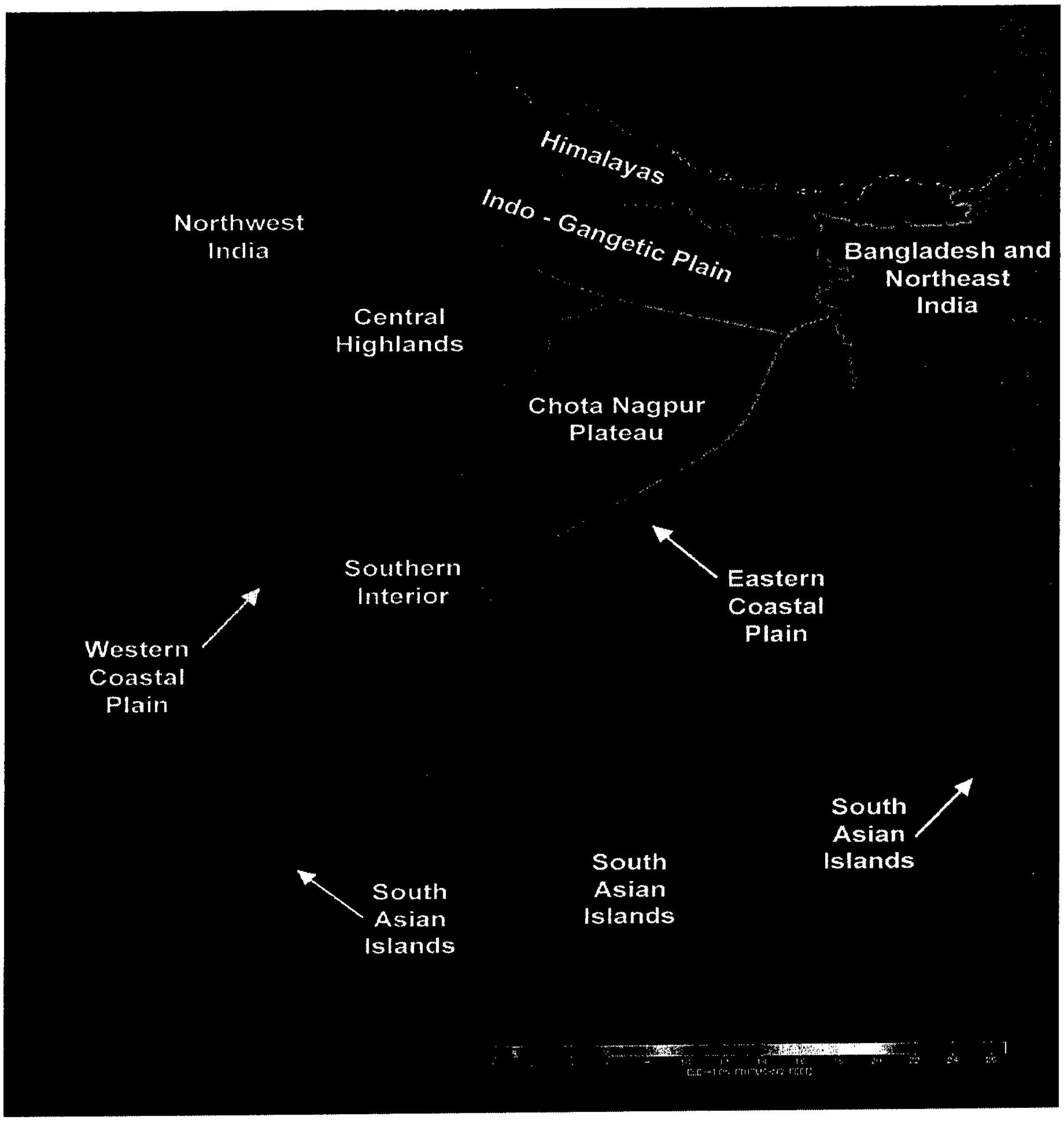


Figure 4-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. December 850-mb winds are easterly at 10 knots. In January and February, they are northeasterly at 5-10 knots. From December through February, the 700-mb winds are easterly at 5-10 knots. At 500 mb, westerly winds at 10-15 knots dominate the season. Westerlies rule at 300 mb; there, they are 25-30 knots. Hyderabad upper-level winds are shown in Figure 4-6.

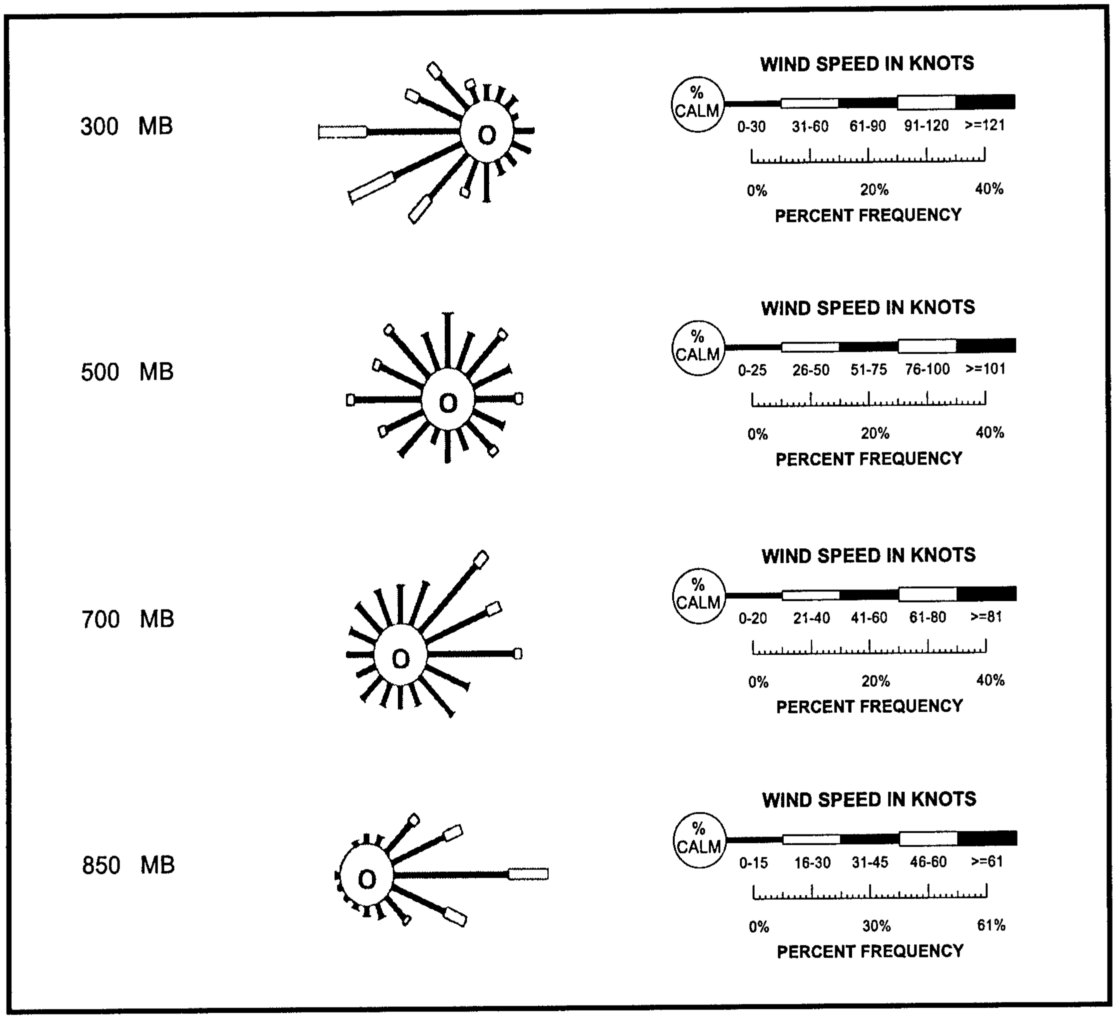


Figure 4-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Hyderabad.

Precipitation. Rain is very light except on the highest peaks and in the southern part of the region in the early part of the season. In December, most places south of 12° N get 1-2 inches (25-51 mm) of rain, but most of the region gets 0.5-0.8 inch (13-20 mm) or less. The most falls in the southern-most highlands, 5-6 inches (127-152 mm) in December. In January and February, rainfall averages well under 0.5 inch (13 mm) per month everywhere but in the southernmost highlands, where it is 1-2 inches (25-51 mm). In the lowlands, rain falls 1-2 days per month in December and January and less than 1 day in February. The northern and central highlands see 2-4 days with rain in December and 1 day or less in January and February. The southern-most highlands get 4-7 days with rain in December and 2-4 in January and February. Thunderstorms are at the annual minimum in this season. They occur 1 day or less per month all season everywhere, the southern highlands included. Although extremely rare, tropical storms moving across the region have dropped as much as 7.5 inches (191 mm) of rain in the southern half. Figure 4-7 shows precipitation amounts and Figure 4-8 shows rain and thunderstorm days.

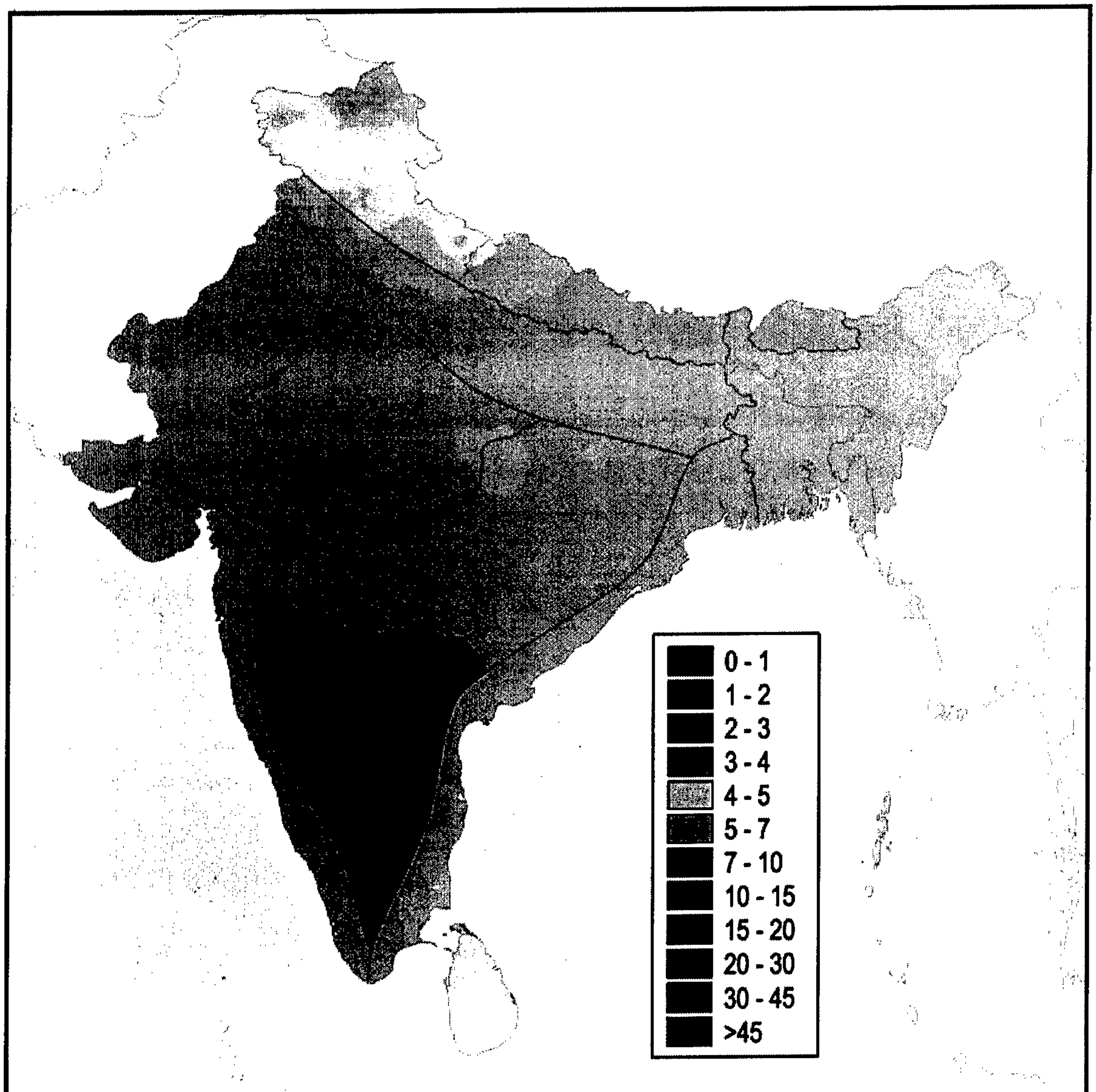


Figure 4-7. January Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

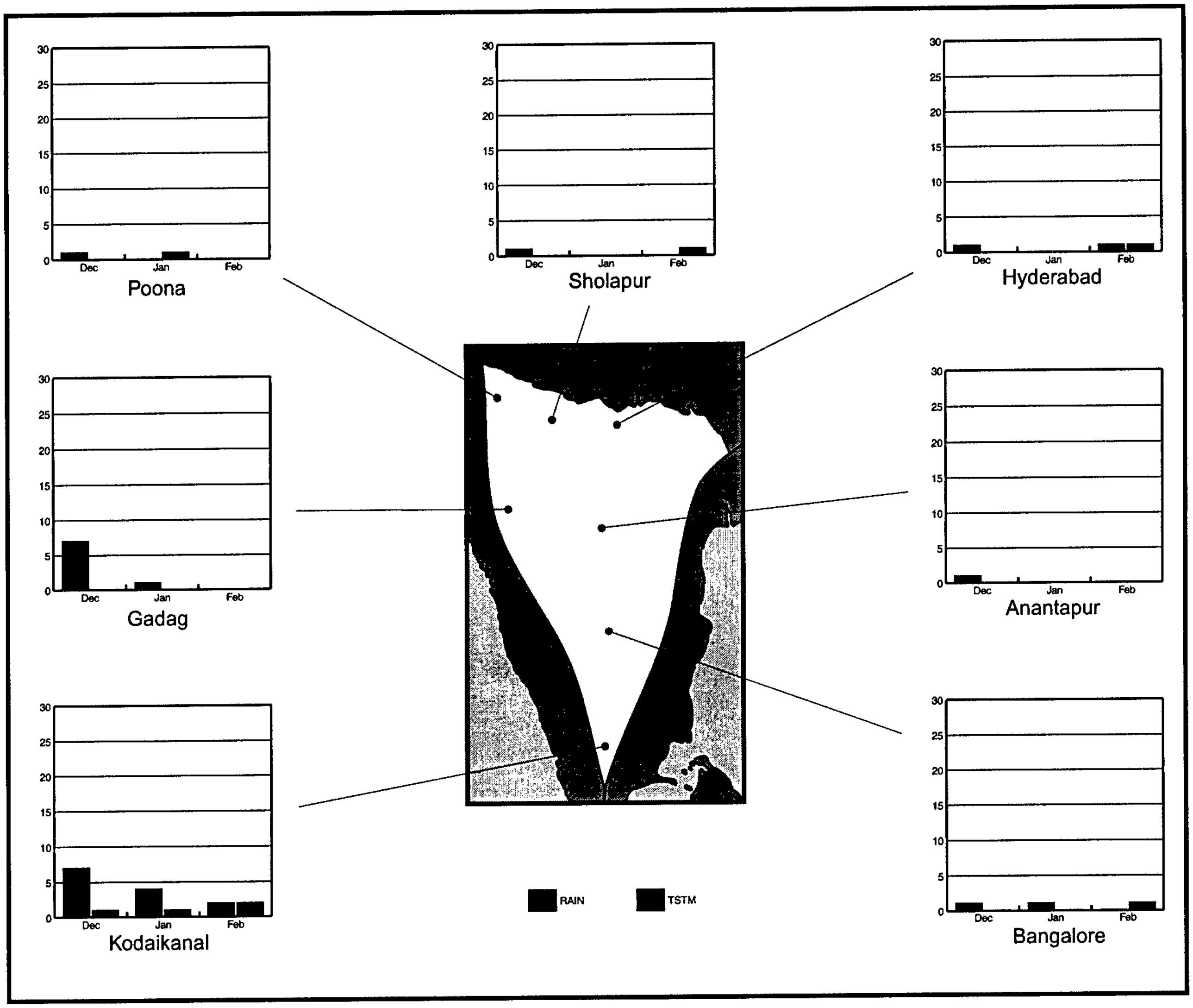


Figure 4-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Diurnal temperature ranges are wider in the interior than near the coast. Temperatures are generally warmest in the south and coolest in the north, except for high elevation sites in the Cardamom Hills. The December and January mean highs are 80° to 85°F (27° to 29°C) in the north and 84° to 88°F (29° to 31°C) in the south. In the high Cardamom Hills, mean highs are 58° to 62°F (14° to 17°C). The December and January mean lows are 52° to 58°F (11° to 14°C) in the north and 64° to 70°F (18° to 21°C) in the south. In the high Cardamom Hills, the mean lows are 44° to 48°F (7° to 9°C) all season. February temperatures rise as the driest months of the year approach. Mean highs are 86° to 95°F (30° to 35°C) everywhere but the Cardamom Hills and mean lows are 60° to 70°F (16° to 21°C) in the south and 55° to 60°F in the north. In the Cardamom Hills, the mean highs are 62° to 66°F (17° to 19°C). Extreme highs are 96° to 102°F (36° to 39°C), with the hottest temperatures in the far south lowlands and the coolest on the regional northwestern rim. Extreme lows are 38° to 45°F (3° to 7°C) in the north and 51° to 55°F (11° to 13°C) in the south. Even in the high Cardamom Hills, the extreme lows fall only to freezing. The extreme low there is 32°F (0°C). See Figure 4-9 for mean highs in January and Figure 4-10 for mean lows.

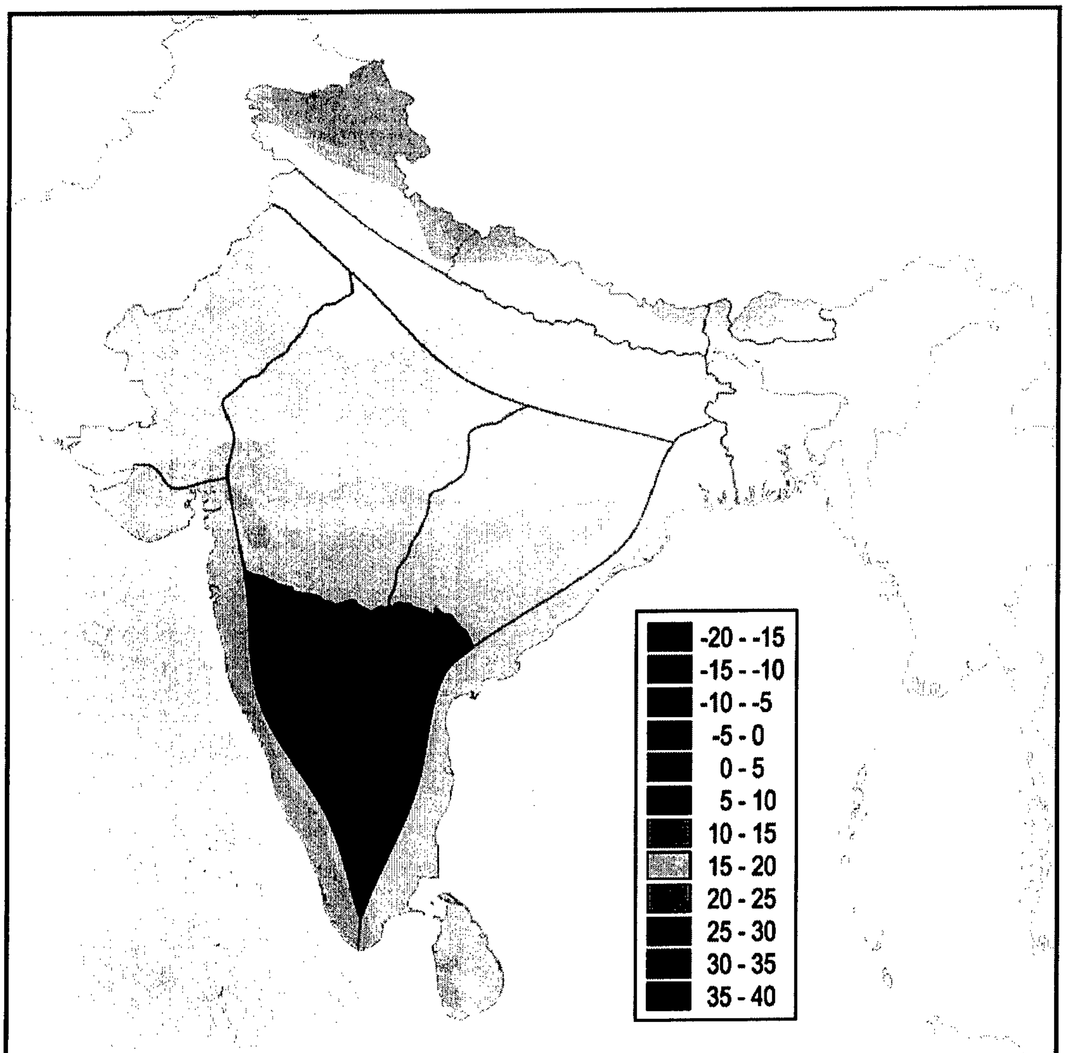


Figure 4-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for January. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

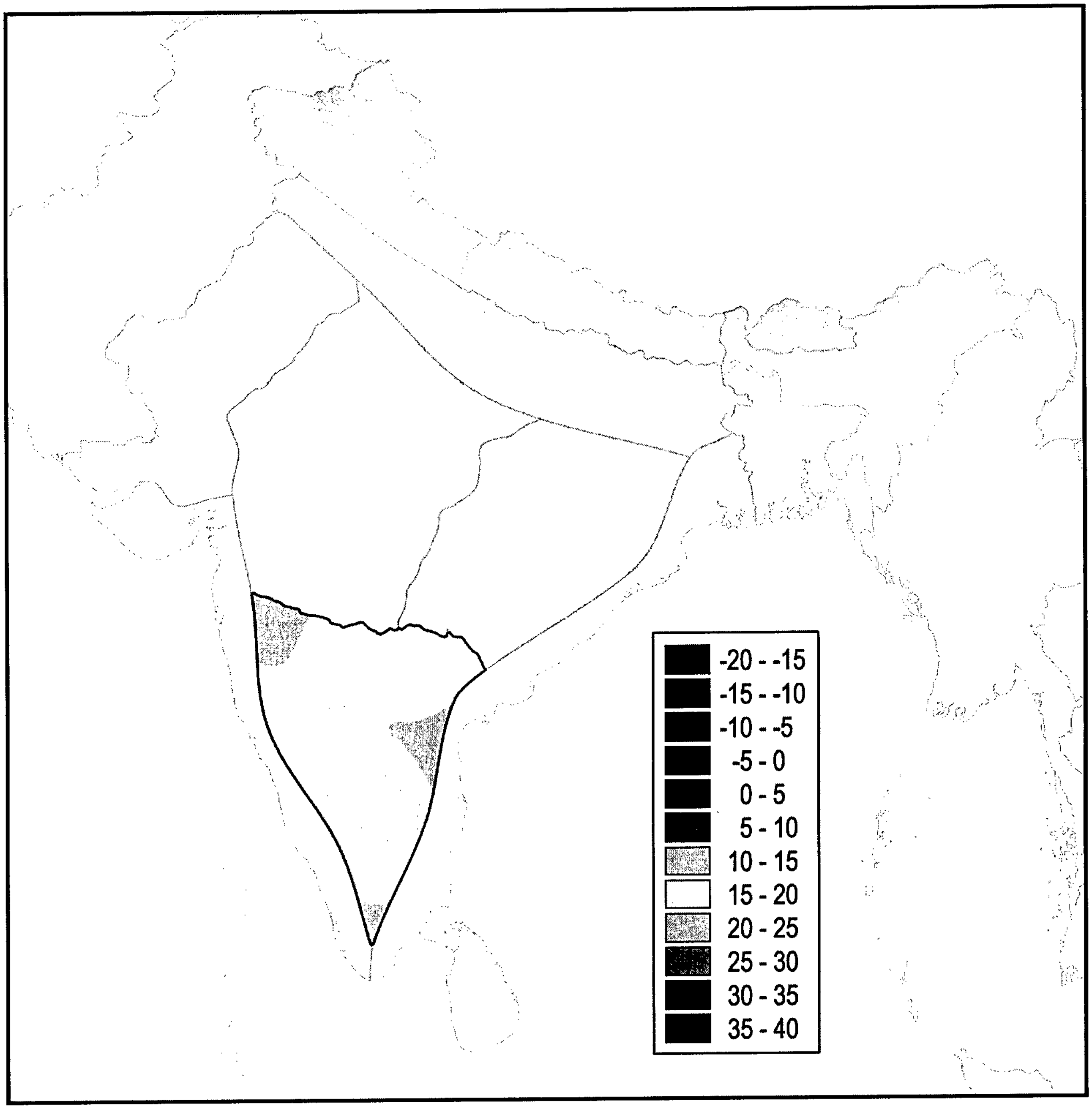


Figure 4-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for January. Daily low temperatures are often higher than the mean. Mean minimum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

Hot Season

General Weather. This period is when the dry weather reaches its peak. The subtropical jet that moved migratory lows through in the winter now lies mostly north of the Himalayan massif. Also, the thermal high over Asia is seriously weakened by March, and the induced leeside trough at the southern foot of the mountains is no longer a favored track for passing lows (western disturbances). This moves the storm track from the southern flanks of the Himalayas to north of the range, and few lows move across northern India as a result. The thermal low over Australia disappears, and the ET heads north with the sun. Wind circulation is confused. All in all, the weather is clearest and driest in these months, and the hottest temperatures occur.

April-May is when the ET crosses over the southern part of the peninsula at the leading edge of the southwest monsoon. There is considerable variance in onset of the southwest monsoon across the region. The rains begin at almost the same time on the southern tip of the peninsula and in the northeast corner of the Bengal basin in mid-May. It takes another month and a half for all of India to be fully under the southwest monsoon regime. The northward travel of the equatorial trough is not a smooth, steady one. It oscillates north and south, moves many miles in surges then retreats, and stagnates in one place for days at a time. In this transition season, "onset vortices" travel along the ET at the leading (northern) edge of the southwest monsoon air mass. These vortices produce rain, rainshowers, and thunderstorms and signal the "monsoon burst" of the changing season. The hottest weather of the year ends with this transition. Although not common, tropical cyclones do develop in the Bay of Bengal in the hot season. Their mean track brings them ashore on the northeastern coast. They are more likely to occur in May, with the ET as it shifts north, than in April.

Sky Cover. March and April have the least cloud cover, but May shows an increase as the southwest monsoon flow approaches. The proportion of low cloud in the total cloud cover increases as the season progresses as well. The southern areas see the increase first. The average day cloud cover is about 35 percent in the north part of the region and 55 percent in the south. Areas nearest the coast see 65 percent cloud cover at mid-season. Diurnally, the most cloud cover occurs in the late morning to early evening hours and the least occurs in the early morning hours. See Figure 4-11 for ceilings below 5,000 feet at representative stations.

Ceilings below 5,000 feet occur most in the Cardamom Hills and in May. In the rain shadow of the Western Ghats (roughly the western third of the region), ceilings below 5,000 feet rarely occur in March and April and occur 15-20 percent of the time from afternoon to early morning in May. The May hours from 0800 and 1400L have the minimum there, ceilings below 5,000 feet occur only 5-10 percent of the time. In the eastern two-thirds of the region, ceilings below 5,000 feet occur 10-15 percent of the time in March and April afternoons and 3-10 percent of the time the rest of the day. In May, the rates rise to 20-30 percent of the time in the afternoons and 10-15 percent of the time the rest of the day.

Ceilings below 1,000 feet rarely occur outside of the high Cardamom Hills, where they occur 20-25 percent of the time all season during the afternoon through evening hours and roughly 5 percent of the time the rest of the day. Bangalore, in the central highlands, rarely has ceilings below 1,000 feet in March and April but gets them 10 percent of the time on May mornings, then not at all the rest of the day.

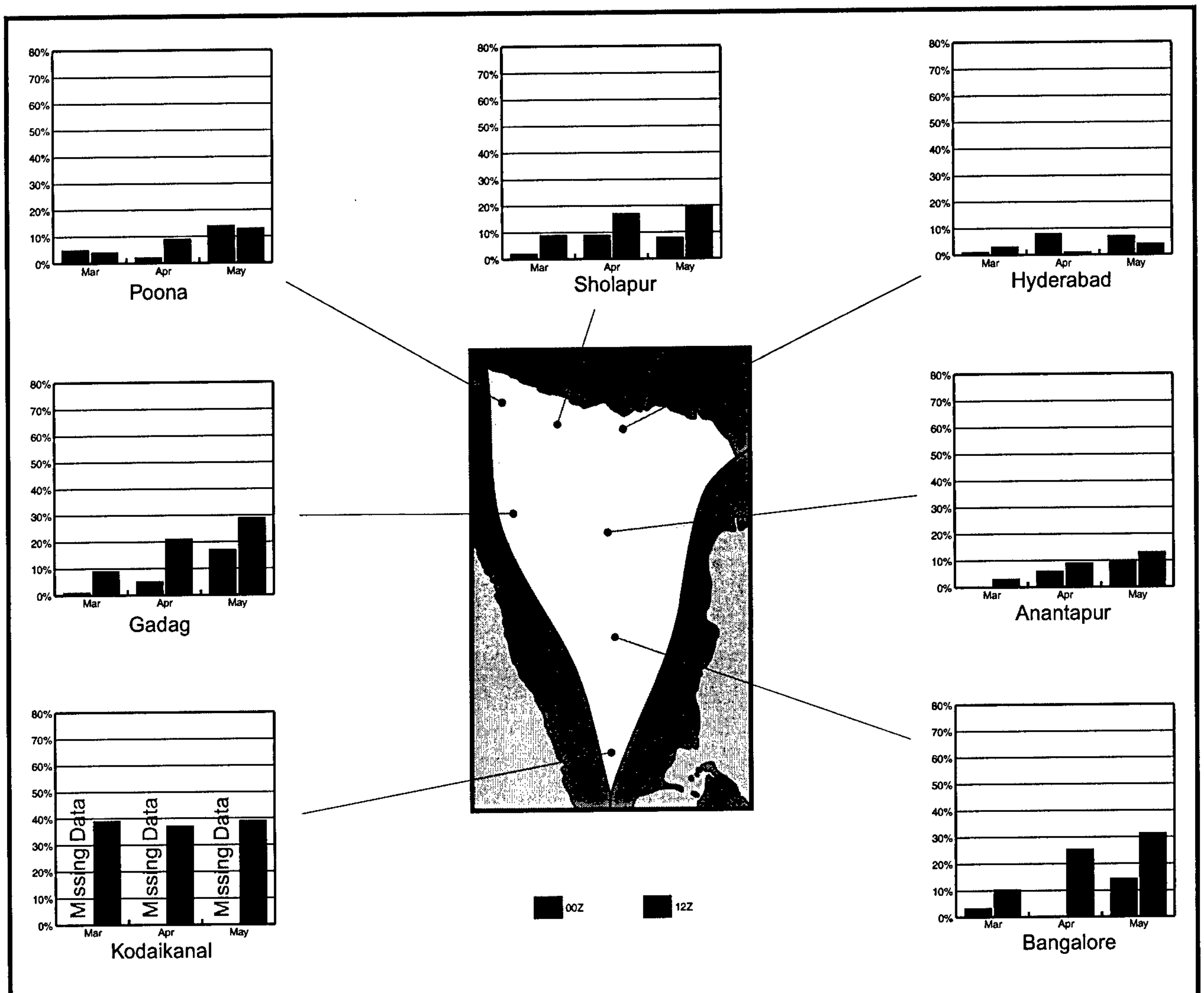


Figure 4-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Morning fog occurs least in this season and dust reduces visibility the most, but visibility below 1 1/4 miles (2,000 meters) occurs rarely. Visibility reduced by dust or smog is localized and rarely goes below 2 1/2 miles (4,000 meters). In May, as the pre-monsoonal rains begin, visibility in the south may be reduced in rainshowers or thunderstorms. See Figure 4-12 for visibility below 4,000 meters at representative stations.

Visibility below 4,000 meters occurs rarely in most of the region. The morning hours in the western highlands (e.g., Poona) have visibility below 4,000 meters 25-30 percent of the time in March, 15-20 percent of the time in April, and rarely in May. The fog dissipates shortly after sunrise and visibility this low occurs only in convective rain the rest of the day. In the Cardamom Hills, visibility below 4,000 meters occurs 10-15 percent of the time in the late afternoon to early evening hours as moisture from the lowlands lifts into the higher elevations. Visibility below 2,000 meters occurs only in the highland areas and not often even there-- 5 percent or less of the time all season.

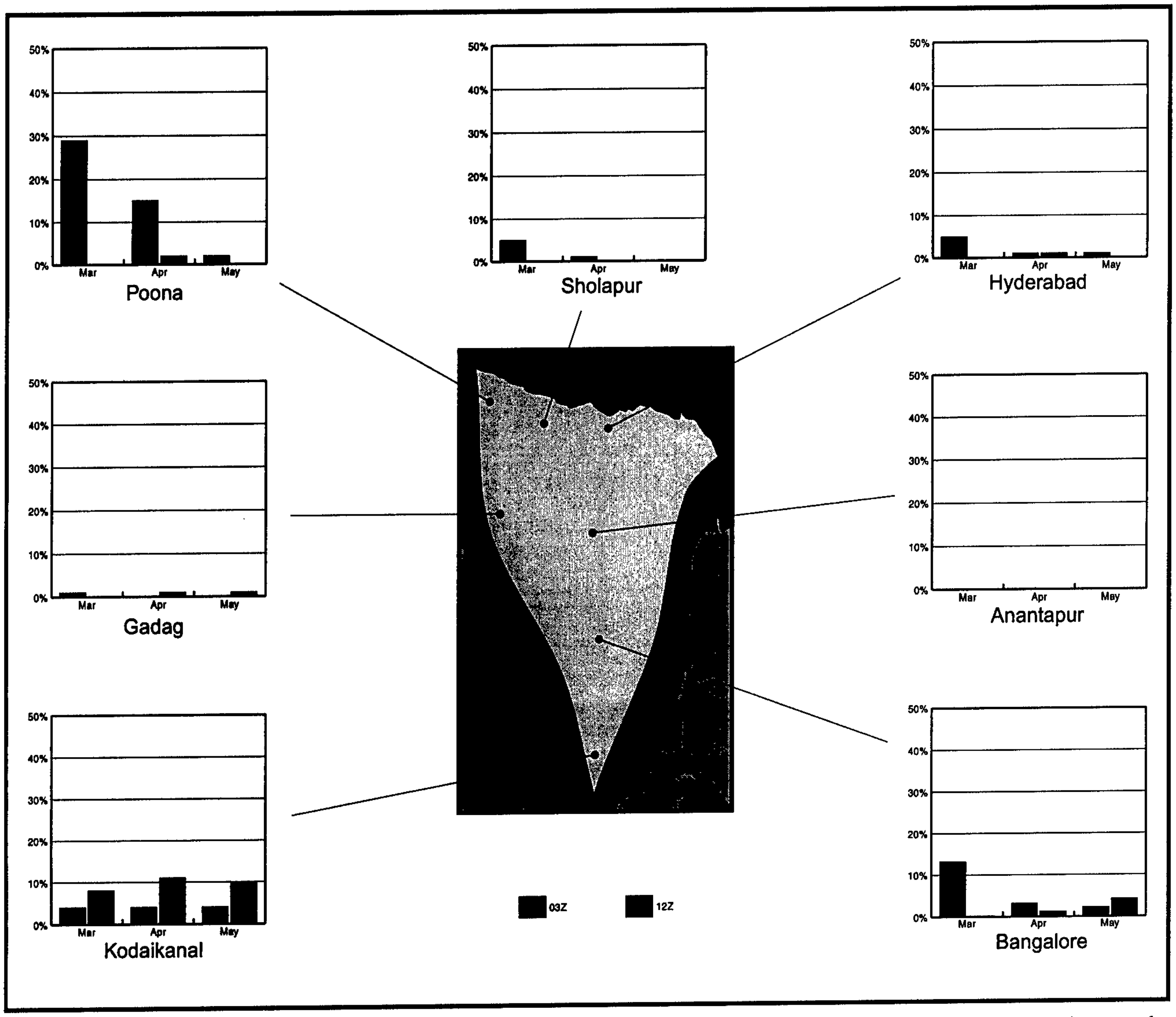


Figure 4-12. Hot Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Surface winds are more locally driven in this season of transition. In many places, winds change direction between day and night. In the lowlands, overnight winds tend to come from the north at 5-10 knots unless some local terrain feature produces drainage winds. During the day, they come from the southeast or east at about the same speed. Anantapur is a classic example; winds there come from the west at night and out of the east during the day. Calms in the lowlands occur 30-50 percent of the time at night and 20-30 percent of the time during the day. Winds in the Western Ghats typically remain out of the west or southwest at all hours. Speeds at night are 5-10 knots and day speeds rise to 10-15 knots. Calms occur there less often than in winter, 60-75 percent of the time at night and 20-30 percent of the time during the day. See Figure 4-13 for surface wind roses for stations in the region.

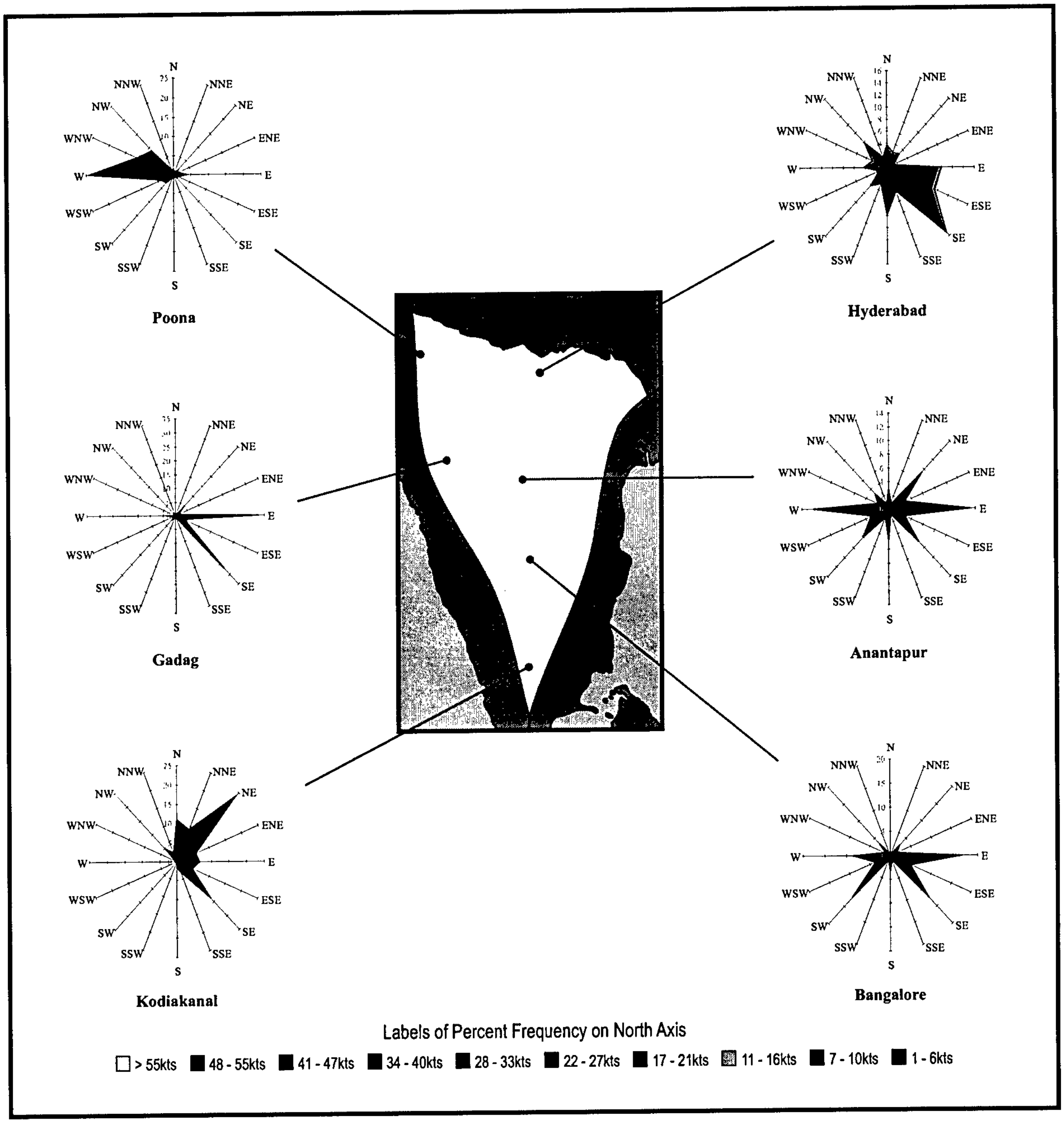


Figure 4-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. In March, 850-mb winds are northeasterly at 5-10 knots. In April and May, the region has variable winds that begin to blow mainly from the west at 5 knots by May. At 700 mb, winds vary from northeast to southeast at 5-10 knots all season. At 500 mb, west to winds blow at 5-10 knots. At 300 mb, west winds at 15-25 knots prevail. The upper-level winds for Hyderabad are shown in Figure 4-14.

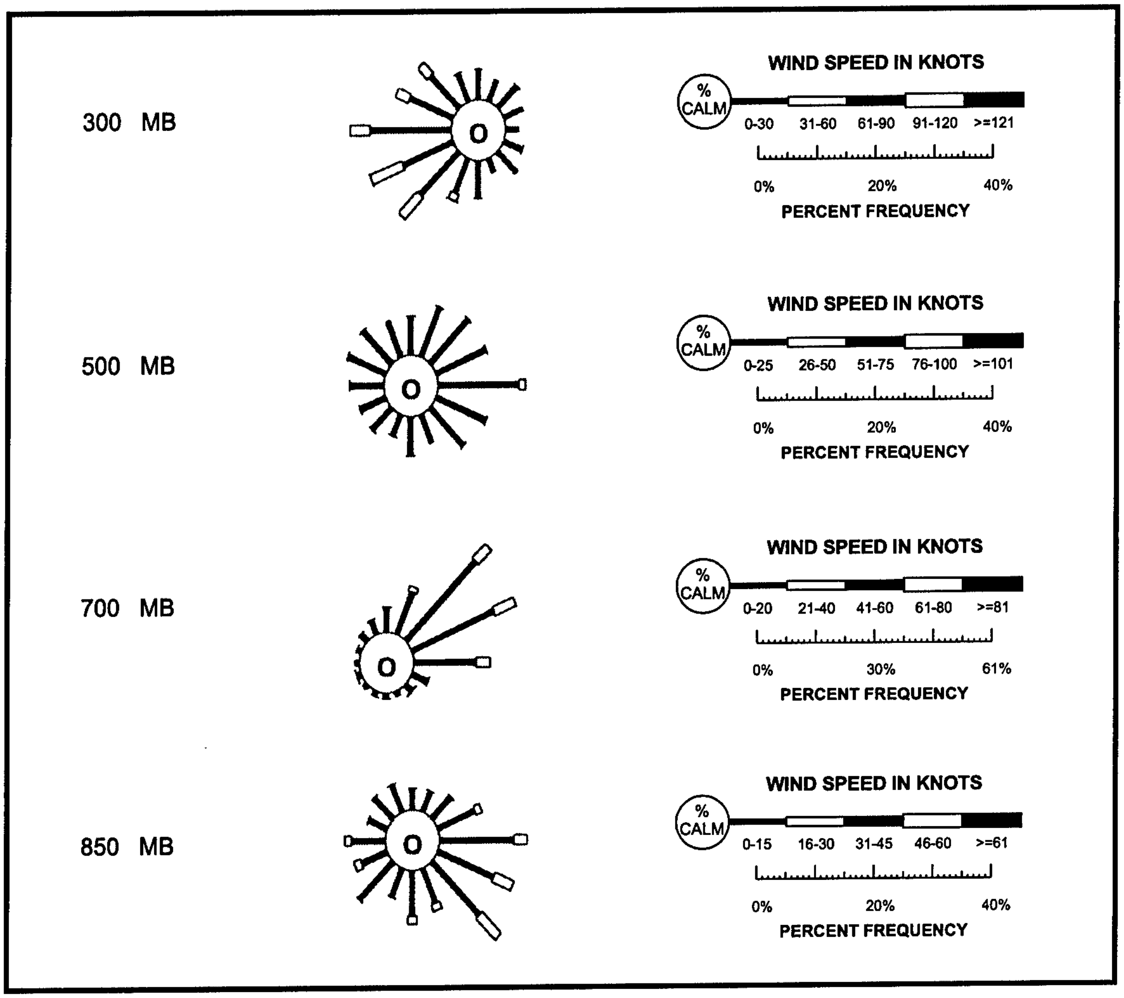


Figure 4-14. April Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Hyderabad.

Precipitation. Precipitation amounts rise through the season from the annual minimum that occurs in March. March amounts are 0.5 (13 mm) inch or less everywhere but in the high Cardamom Hills, where 1.5-2 inches (38-51 mm) of rain falls. Except in the rain shadow of the Western Ghats, roughly the western quarter of the region, April amounts rise to 1.5-2.5 inches (38-64 mm) and May amounts rise again to 2-4 inches (51-102 mm). In the rainshadow, April amounts remain at 0.5 inch (13 mm) or less and May amounts only increase to 1 inch (25 mm) or less. More rain falls in the high Cardamom Hills than anywhere else. In April 4-6 inches (102-152 mm) of rain occurs here and in May 6-8 inches (152-203 mm) occurs. In this region, rain falls 1 day or less in March, 1-3 days in April, and 2-8 days in May, with the most rain days in the central highland and southeastern lowland areas. The Cardamom Hills area has more rain because of its greater exposure to moist flow. It rains there 3-5 days in March, 8-10 days in April, and 11-15 days in May. Early season tropical storms track across the southern half of the region. There have been rare events in which more than 6 inches (152 mm) of rain fell in a single 24-hour period.

Thunderstorm activity peaks in April-May and September-October and occurs both as air mass storms and in association with the ET as it moves north. In the north half of the region, thunderstorms occur 1-3 days in March and 2-6 days in April and May, with the least in the rainshadow of the Western Ghats. In the central highlands and the southern lowlands, they occur 2-4 days in March, 8-11 days in April, and 9-14 days in May. In the Cardamom Hills, they occur the most, 6-8 days in March and 14-18 days in April and May. Figure 4-15 shows precipitation amounts and Figure 4-16 shows rain and thunderstorm days at representative stations.

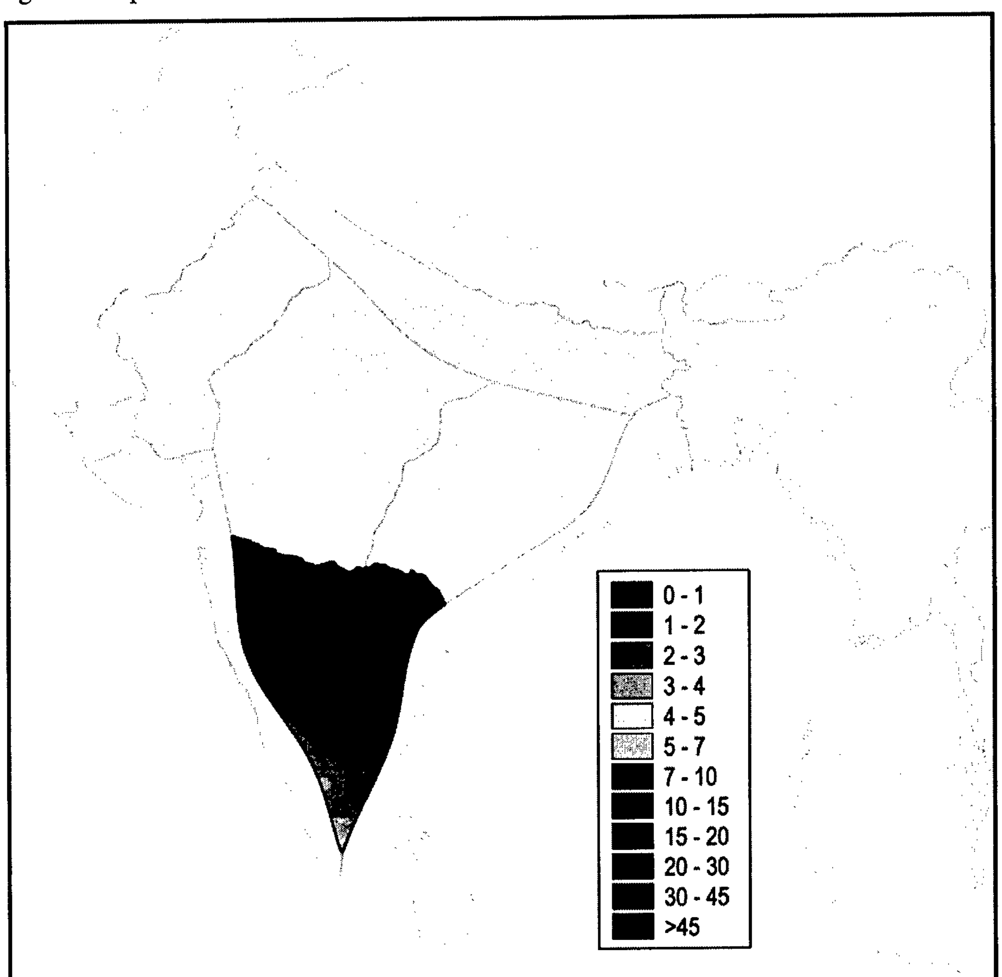


Figure 4-15. April Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

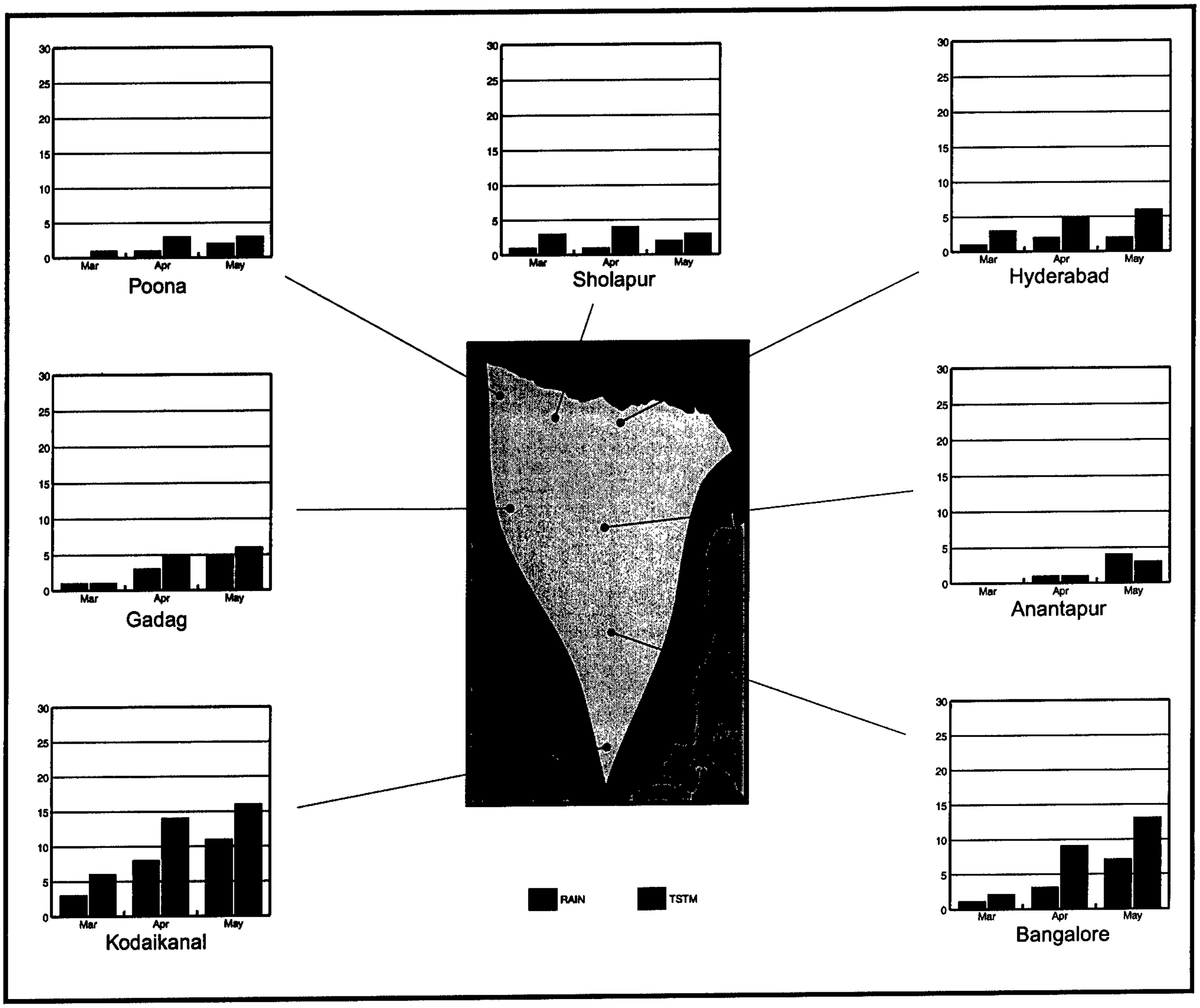


Figure 4-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. April and May are the hottest months of the year. March mean highs are 91° to 96°F (33° to 36°C) in the north half of the region and 94° to 101°F (34° to 38°C) in the south half. In April, they rise to 94° to 100°F (34° to 38°C) in the north and 98° to 106°F (37° to 41°C) in the south. Temperatures cool in the south in May as the early rains begin before the end of the month. In the north, mean highs rise to 98° to 105°F (37° to 41°C); in the south they cool to 92° to 95°F (33° to 35°C). Temperatures cool moist adiabatically, so the southern hills average mean lows of 64°-68°F (18° to 20°C) all season. The March mean lows in the north half of the region are 62° to 68°F (17° to 20°C); in the south, they are 68° to 74°F (20° to 23°C). In April, they rise to 68° to 75°F (20° to 24°C) in the north and 72° to 79°F (22° to 26°C) in the south. By May, cloud cover begins to limit nocturnal cooling and southern mean lows rise to 78° to 83°F (26° to 28°C). The mean lows in the north remain the same from April to May. In the high

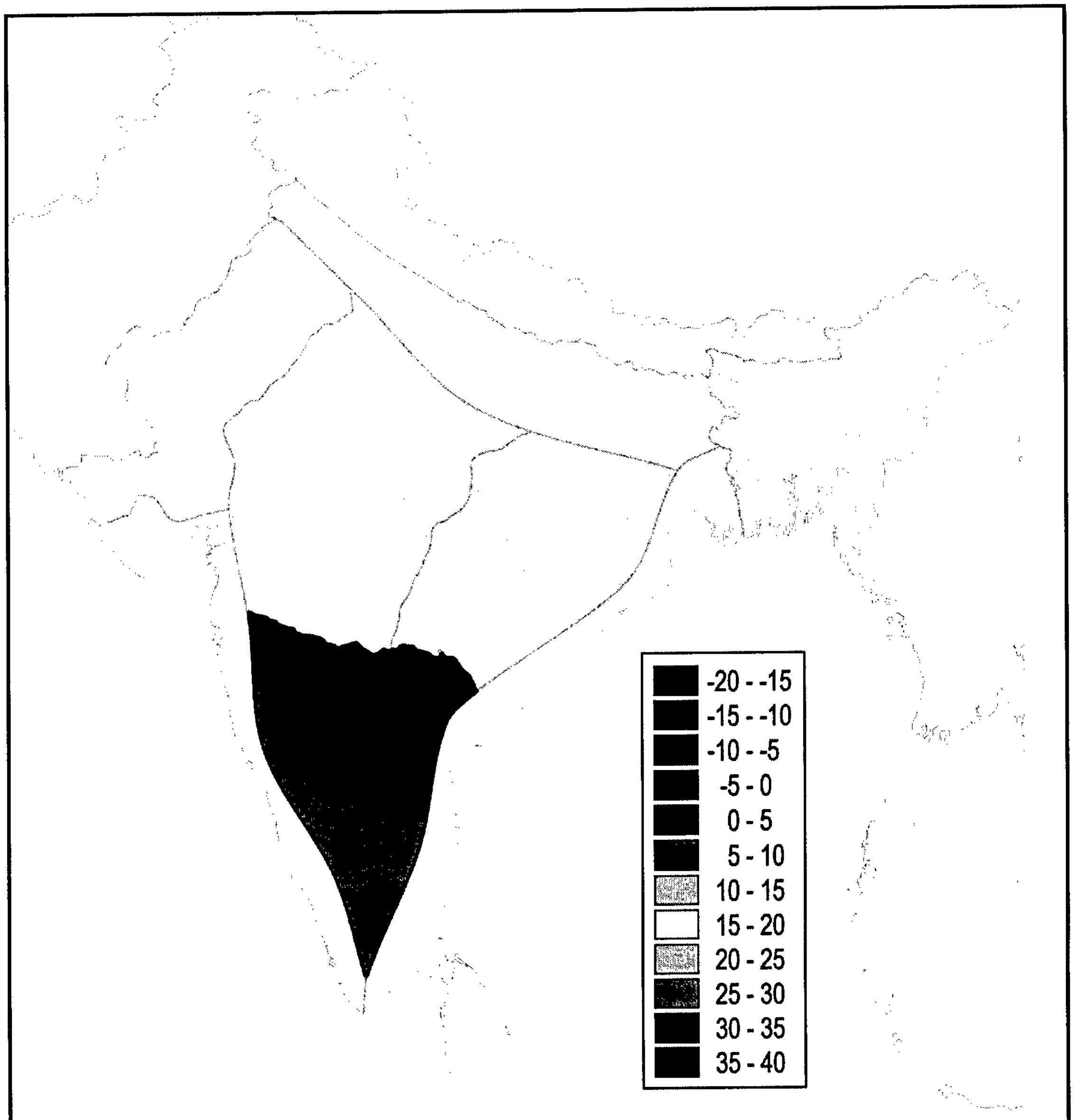


Figure 4-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

southern hills, the mean lows average 50° to 55°F (10° to 13°C) all season, slightly warmer in May than in March. The extreme highs are 100° to 110°F (38° to 44°C) in March and April, and 109° to 117°F (43° to 47°C) in May. In the southern hills, the coolest part of the region, they do not exceed 82°F (28°C). The hottest extreme highs are in the northwestern corner of the region and are most likely under drought conditions in El Niño years. The March extreme lows are 42° to 55°F (6° to 13°C) in the north and 56° to 63°F (13° to 17°C) in the south. In April and May, they are 51° to 57°F (11° to 14°C) in the north and 55° to 67°F (13° to 19°C) in the south. In the southern hills, the extreme lows are 36° to 38°F (2° to 3°C) in March, and 45° to 48°F (7° to 9°C) in April and May. Outside of the southern hills, the coldest extreme lows occur in the northwestern corner of the region, in the rainshadow of the Western Ghats. Figure 4-17 shows mean highs and Figure 4-18 shows mean lows.

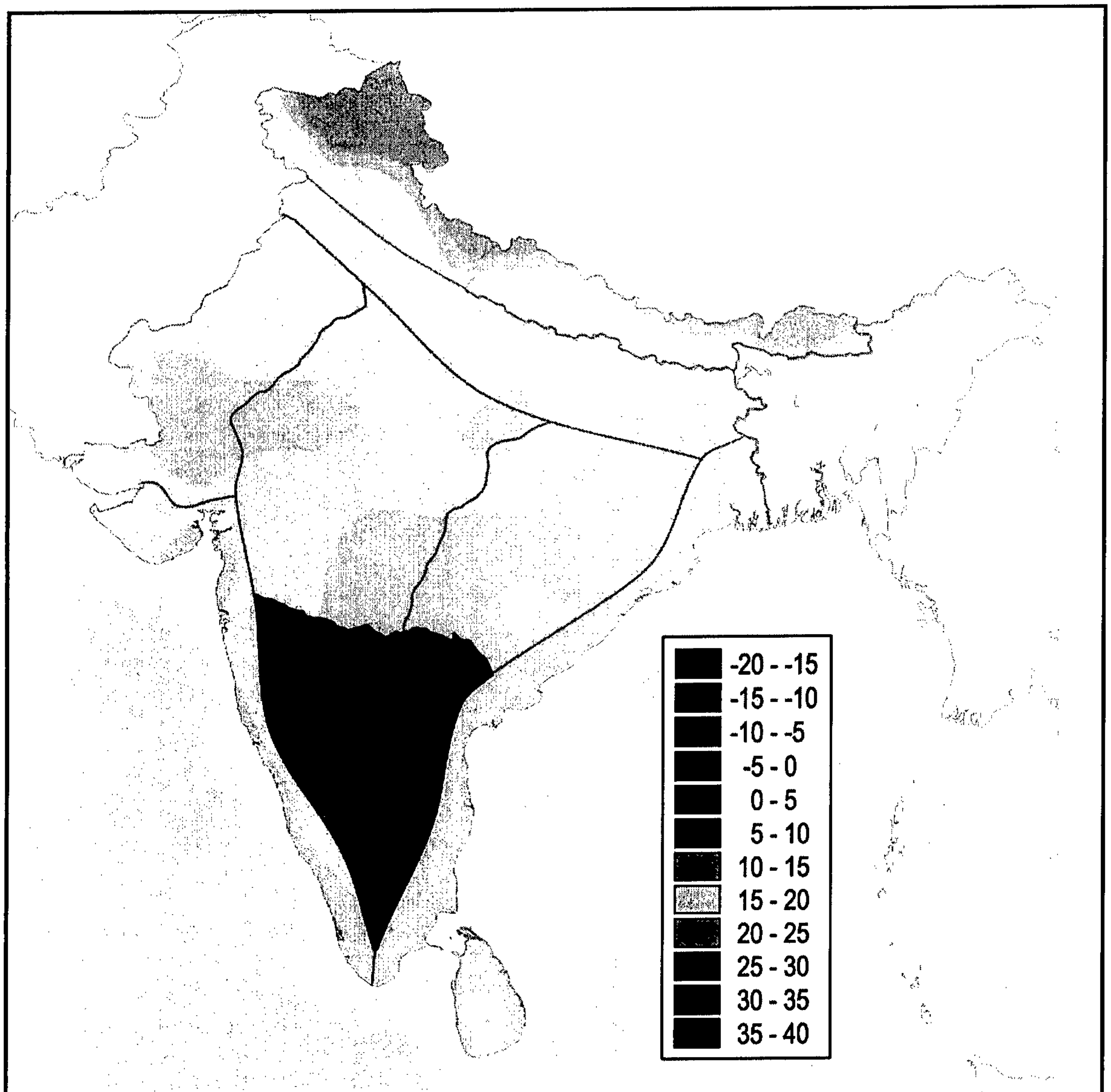


Figure 4-18. April Mean Minimum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for the month. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. The ET moves into the area along with overall southwest flow. Although generally thought to begin in June, the monsoon actually begins as early as mid May on the southern tip of the peninsula and in the northern areas. The rest of the region gets the southwest monsoon in stages from south to north. By early June, the whole region is under southwest monsoon flow. By July and August, the ET is as far north as it gets and easterly flow aloft is almost to the foot of the Himalayas. The India-Myanmar trough sets up in this season. This southwest-northeast oriented trough develops over the Bay of Bengal and is a prime breeding ground for monsoon depressions. Easterly waves and other tropical disturbances are enhanced when they make their way into this convergence zone and sometimes develop into full-blown tropical cyclones.

Mean tropical cyclone tracks are generally in the northern Bay of Bengal. In June and July, most storms tend to make landfall in the northeastern corner of the bay. In August through October, the tracks shift south slightly.

The equatorial westerlies are a hallmark of the southwest monsoon season. Created by deflected outflow of the South Indian Ocean high, these low-level winds spread out over the north Indian Ocean. At the same time these winds begin to flow, the Somali jet develops. This low-level jet transports Southern Hemispheric air across the equator. This warm, moisture-laden air makes the southwest monsoon season rainy. The tropical easterly jet (TEJ), which is a southwest monsoon feature, provides an upper-level exhaust for Bay of Bengal convection. The bay is a prime zone for the development of tropical cyclones, monsoon depressions, and other cyclonic storms. Fortunately, storms in the Bay of Bengal are so confined in the enclosed bay, they do not become as powerful as open ocean storms can. They can still carry high winds, heavy surf, and vast amounts of precipitation. Most of the precipitation in Bay of Bengal coastal areas occurs in the southwest monsoon season.

The deep, wide band of upper-air easterlies overlies the equatorial westerlies. During this season, the easterlies are strongest and spread farthest north, almost to the foot of the Himalayas. Easterly waves ride this powerful current of air and trigger off the development of monsoon depressions and tropical cyclones. By the end of the season, the band of easterlies retreats southward toward the equator.

Thermal lows set up over the central Indian subcontinent and over the Tibetan Plateau. The Indian low becomes part of the greater Asiatic low and trough that extends from northwestern India to the Sahara. This is a source region for migratory lows that move across the subcontinent and into the Bay of Bengal. Over-lying the Tibetan low is the Tibetan anticyclone, which develops in the zone between the strong, deep westerlies of the Northern Hemispheric midlatitudes and the strong, deep easterlies of the low latitudes. The stronger the thermal low, the stronger the anticyclone. The southern edge of this anticyclone is a prime area for the development of monsoon depressions and other cyclonic storms, especially in the Bay of Bengal. It is the cyclonic storms that develop in the Bay of Bengal that provide the rains for this region, as general southwest monsoon flow is offshore (equatorial westerlies) and carries little moisture to the area.

Sky Cover. The skies are cloudy in this season, an average of 65-75 percent covered; however, the occurrence rate of very low ceilings is still low everywhere but in the higher elevations. In July and August, 20-30 afternoons per month are cloudy almost everywhere and clear periods are infrequent and short. There is little diurnal variation in cloud amounts. Low and mid-level stratiform clouds dominate. June and September are less cloudy, however, the mean cover is still 55-65 percent over most of the area. In the southernmost areas, 75 percent cover persists through the whole season. Above 6,000-7,000 feet (1,800-2,100 meters) elevation, mountain peaks are commonly cloud-cloaked all season, especially in the Cardamom Hills. Figure 4-19 shows ceilings below 5,000 feet at representative stations.

Ceilings below 5,000 feet occur more in the southern and western parts of the region than in the northern and eastern parts. At most locations, the highest frequency is in the morning hours 2-3 hours after sunrise. At that time, ceilings below 5,000 feet occur 60-70 percent of the time in June and September and 75-85 percent of the time in July and August. In the afternoon, the average drops to 35-45 percent of the time in June and September

and 55-65 percent of the time in July and August. Overnight ceilings below 5,000 feet occur 10-20 percent of the time all season, except at higher elevations, where they rarely occur less than 25 percent of the time and average 35-45 percent of the time. Northern lowland locations, such as Hyderabad, have the least cloud cover. Overnight through sunrise, ceilings below 5,000 feet occur 5-10 percent of the time in June, 30-40 percent of the time in July and August, and 15-25 percent of the time in September. During the day, they occur 15-25 percent of the time in June, 50-60 percent of the time in July and August, and 20-30 percent of the time in September.

Ceilings below 1,000 feet occur above 1,500 feet (450 meters) elevation, the most in the southern-most highlands. The least low cloud occurs in the rain shadow of the Western Ghats and in the northwestern corner of the region. Poona, for example, never gets ceilings below 1,000 feet, and Gadag, farther south in the rainshadow area, only gets them on rare occasions. Below 1,500 feet (450 meters) elevation, they occur only with rainshowers or thunderstorms. In locations between 1,500 and 3,500 feet elevation (450-1,100 meters), ceilings below 1,000 feet occur 35-45 percent of the time in the mornings of June and September and 50-60 percent of the time in July and August. Above that, they occur 10-20 percent of the time in the mornings all season. The situation reverses in the afternoon. Between 1,500 and 3,500 feet (450-1,100 meters), they occur 5-10 percent of the time in June and September and 10-15 percent of the time in July and August. Above that, they occur 30-40 percent of the time in June and September and 45-55 percent of the time in July and August.

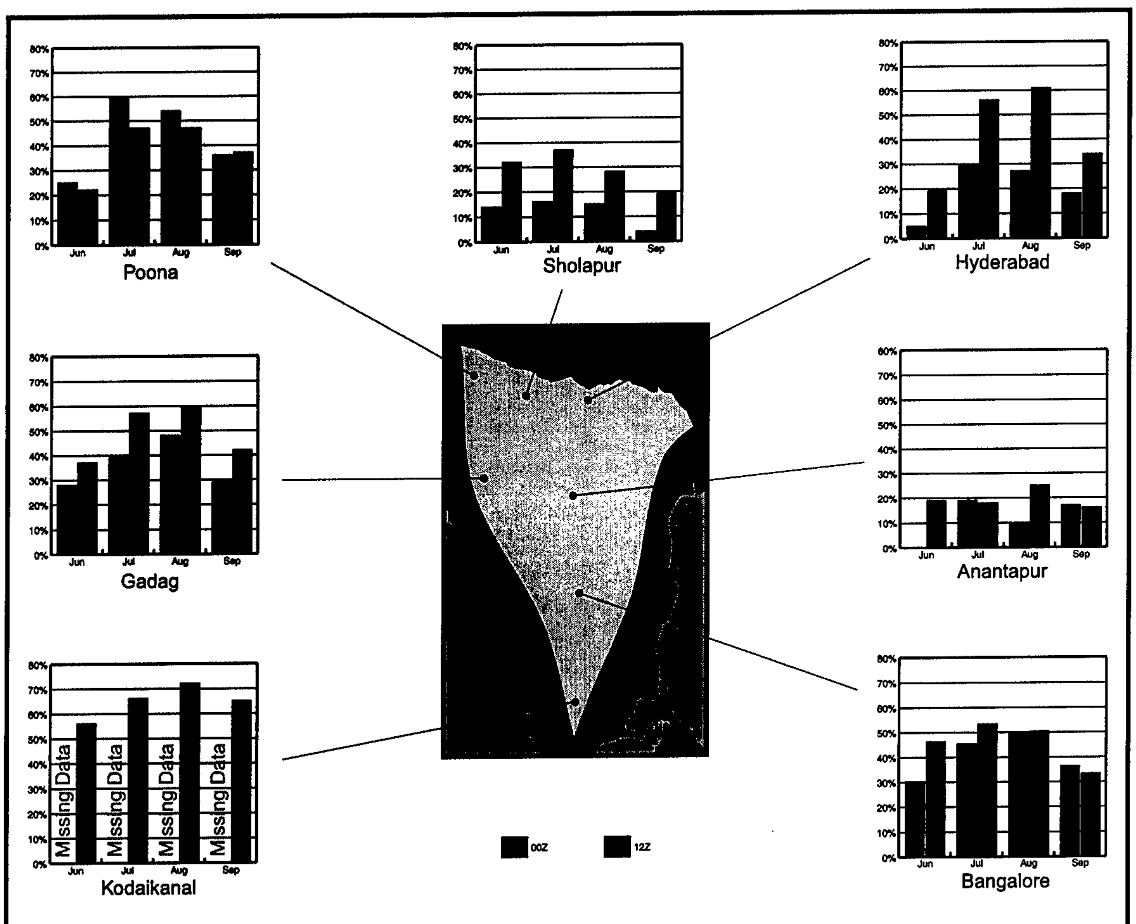


Figure 4-19. Southwest Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility is reduced in heavy rains during rainshowers or thunderstorms but the reduction is short-lived. Dust restrictions do not occur in a normal southwest monsoon season, but they can persist in years of drought. Visibility is rarely below 2 1/2 miles (4,000 meters) outside of rain events. Figure 4-20 shows visibility below 4,000 meters at representative stations.

Visibility below 4,000 meters occurs mainly at high elevations and more in the mornings than the rest of the day. Below 1,500 feet (450 meters) visibility below 4,000 meters occurs only with rainshowers and thunderstorms. Between 1,500 and 3,000 feet (450-1,000 meters) elevation, morning visibility below 4,000 meters occurs 5-15 percent of the time, with the most in July and August. By 2-3 hours after sunrise, conditions improve and it occurs only 5 percent of the time or less all season. Above 3,500 feet (1,100 meters), and progressively more with elevation, the worst visibility of the day occurs in the afternoon. In the mornings, visibility below 4,000 meters occurs 5-15 percent of the time. In the afternoon, though, it occurs 25-35 percent of the time in July through September and only 14-20 percent of the time in June. This restriction is in fog that is actually cloud lifting from lower levels.

Visibility below 1 1/4 miles (2,000 meters) occurs only at high elevations and more in the afternoons than in the morning. It occurs 5 percent of the time or less in the mornings. In June, visibility below 2,000 meters occurs 5-10 percent of the time. In July through September, it occurs 15-25 percent of the time. As mountain peaks are commonly cloud-cloaked above 6,000-7,000 feet (1,800-2,100 meters), visibility above that level remains low all season in cloud.

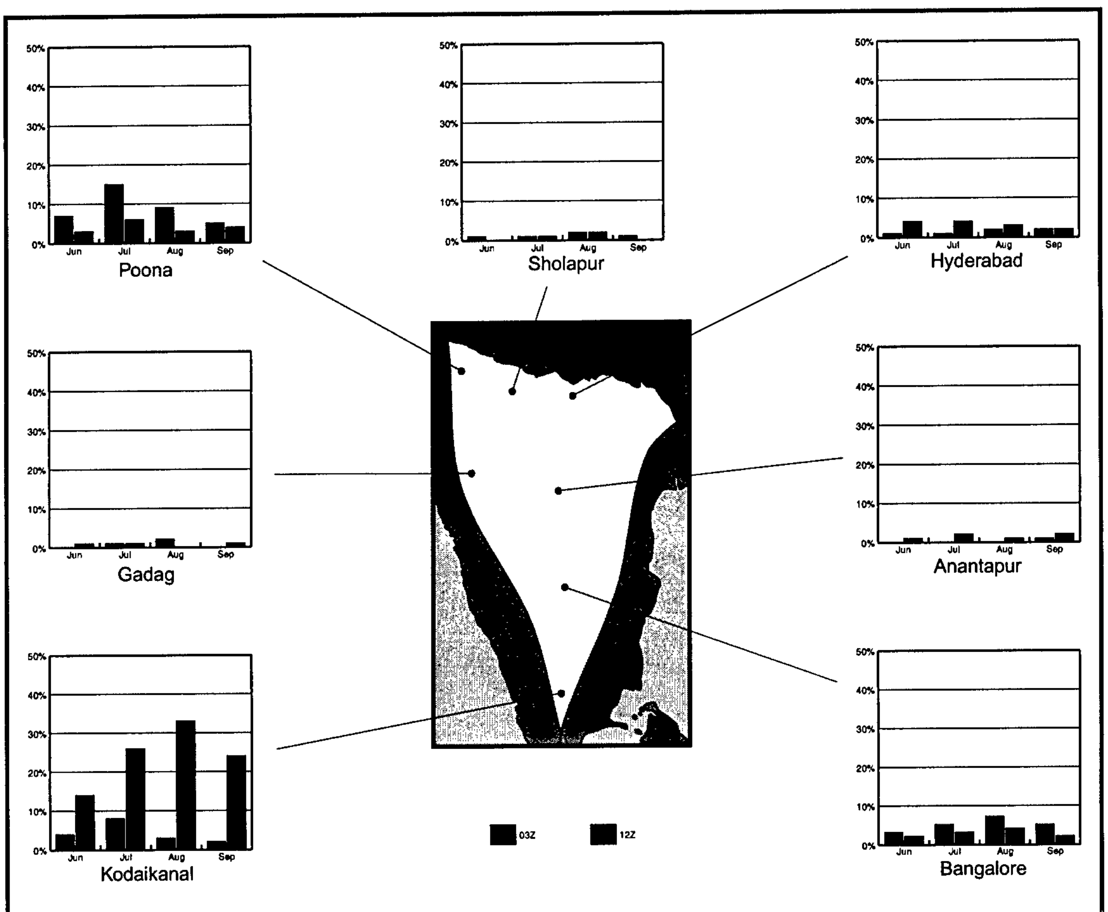


Figure 4-20. Southwest Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Although terrain features influence winds, most places have consistent, west to southwest winds at all hours. This season has the lowest rate of calms of the year as well. Calms occur 5-10 percent of the time at all hours, with most at night. Speeds in the lowlands are 5-10 knots at night and 10-15 knots during the day. At higher elevations speeds are higher, 8-12 knots at night and 12-18 knots during the day. Above 3,000 feet (1,000 meters) elevation, daytime winds often reach 25-30 knots. Figure 4-21 shows surface wind roses for representative stations.

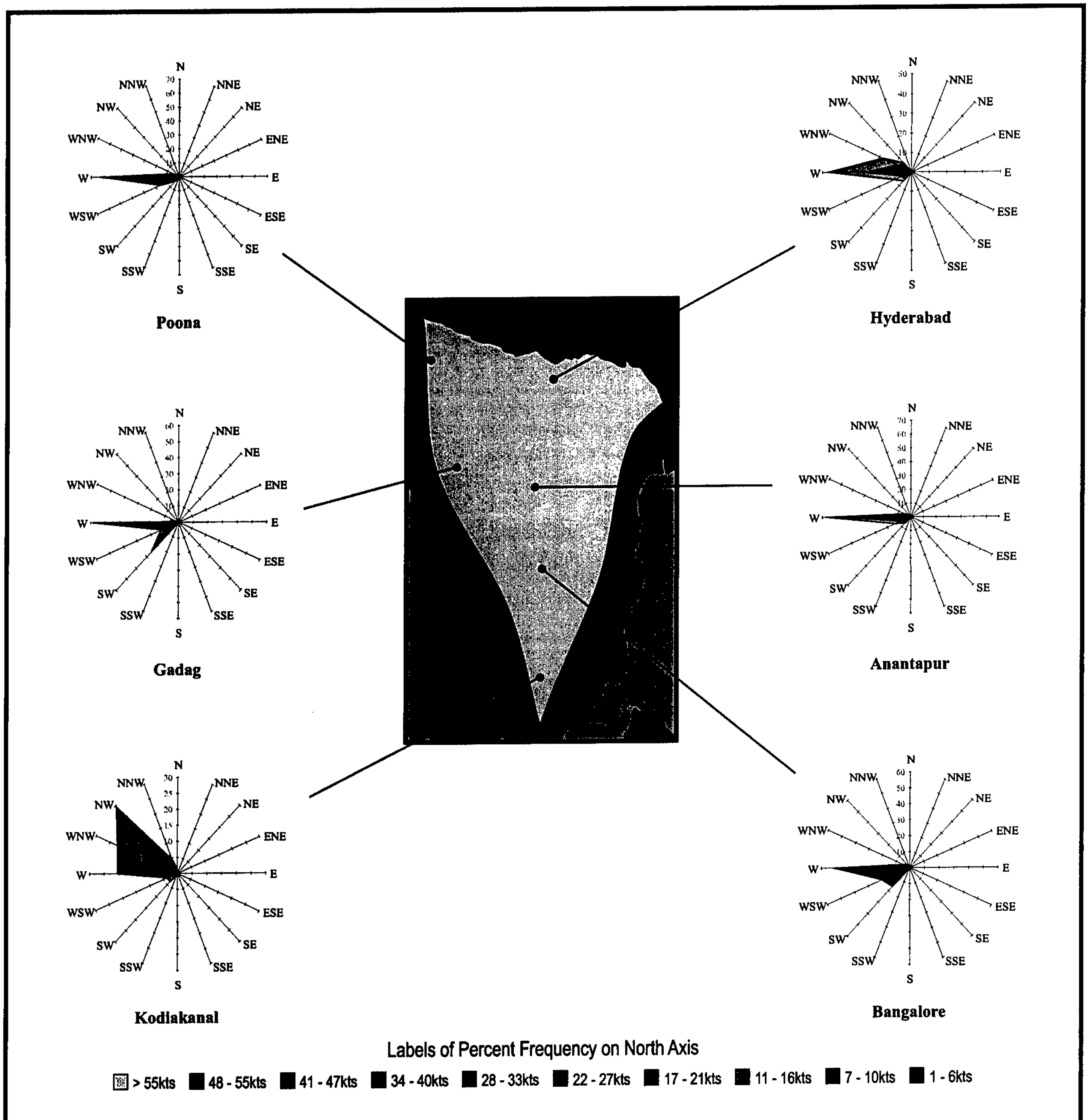


Figure 4-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Winds at 850 mb are westerly at 20 knots. The June 700 mb winds are from the west at 15-20 knots for the whole season. At 500 mb, the region has variable winds that generally come out of the west at 10 knots all season. The 300 mb winds remain from out of the east at 10-15 knots all season. August wind speeds rise to 20 knots from the same direction. Figure 4-22 shows the upper-level winds at Hyderabad.

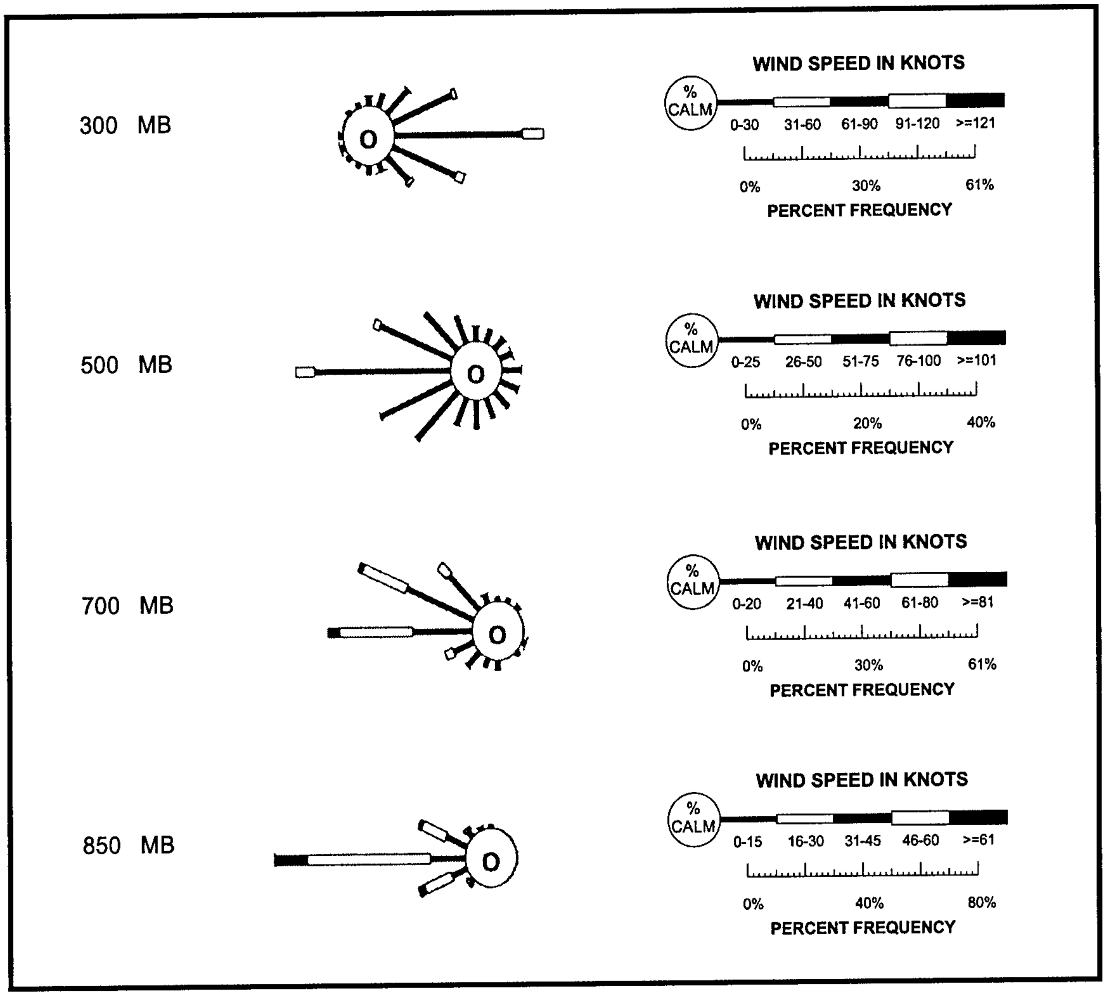


Figure 4-22. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Hyderabad.

Precipitation. As the southwest monsoon moves into an area, it is often heralded by "monsoon bursts" or heavy showers and thunderstorms at the southern end of the peninsula. These heavy rain events can bring 2-3 inches (51-76 mm) of rain in a single event. These bursts of rain alternate with partial or general breaks. There is a wide range in monsoon rainfall from one area to another primarily caused by terrain features that either block or divert southwest monsoonal flow. Although the Western Ghats block low-level southwestern flow, they are not tall enough to entirely block moisture from entering the interior; they just shear off the low-level moisture. Precipitation averages 2-5 inches (51-127 mm) in June just about everywhere. The most falls in exposed locations and the least in sheltered areas. In July and August, the region gets 3-7 inches (76-178 mm), the most in exposed locations. In September, the average rises to the annual maximum, 5-8 inches (127-203 mm). Extreme amounts of rain are associated with monsoon depressions or tropical cyclones of varying intensities. The most rain ever recorded in a single 24-hour period in this region occurred at Belgaum, where 11 inches (279 mm) of rain fell in August.

The most rain and rain days occur at stations close to the ridge line of the Western Ghats. Belgaum, high on the west-central edge of the region, gets 13 days of rain in June, 22 days in July, 18 in August, and 9 in September. In that time, it gets 8-10 inches (203-254 mm) of rain in June, 18-22 inches (457-554 mm) in July, 9-12 inches (229-305 mm) in August and 4-6 inches (102-152 mm) in September. This is typical of the ridgeline locations above the rainshadow. In contrast, the rest of the region gets 7-12 rain days per month all season. Thunderstorms occur with the ET and as air mass convection. Although rainshowers occur somewhere in the region every day, thunderstorms occur less often. Thunderstorms occur an average of 3-6 days in June and September, and 1-3 days in July and August. Exceptions are in the southern and central highlands, where the number rises to 5-10 thunderstorm days, with the most in September and June (in that order) in the high Cardamom Hills. Figure 4-23 shows precipitation amounts and Figure 4-24 shows rain and thunderstorm days for representative stations.

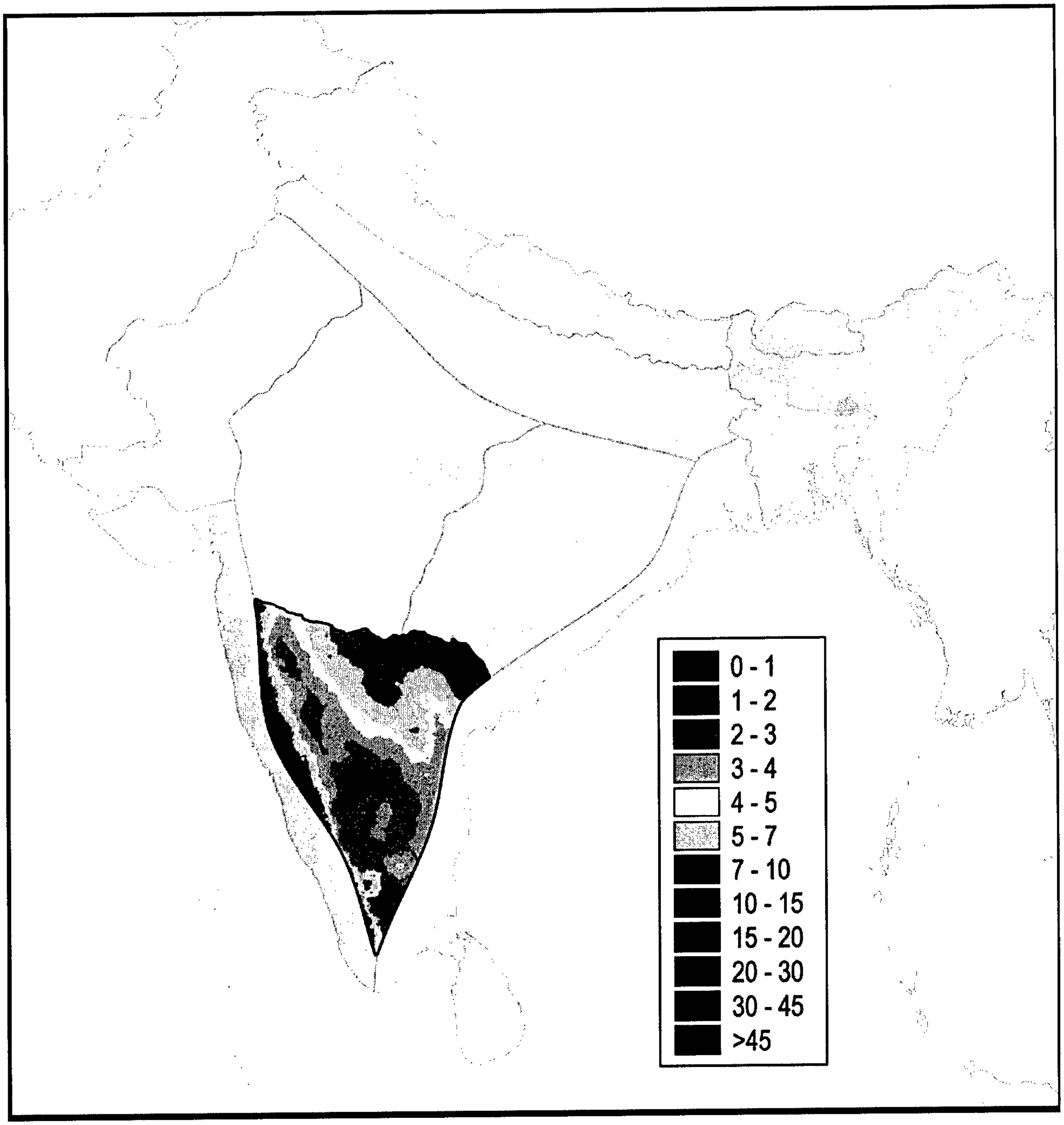


Figure 4-23. July Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

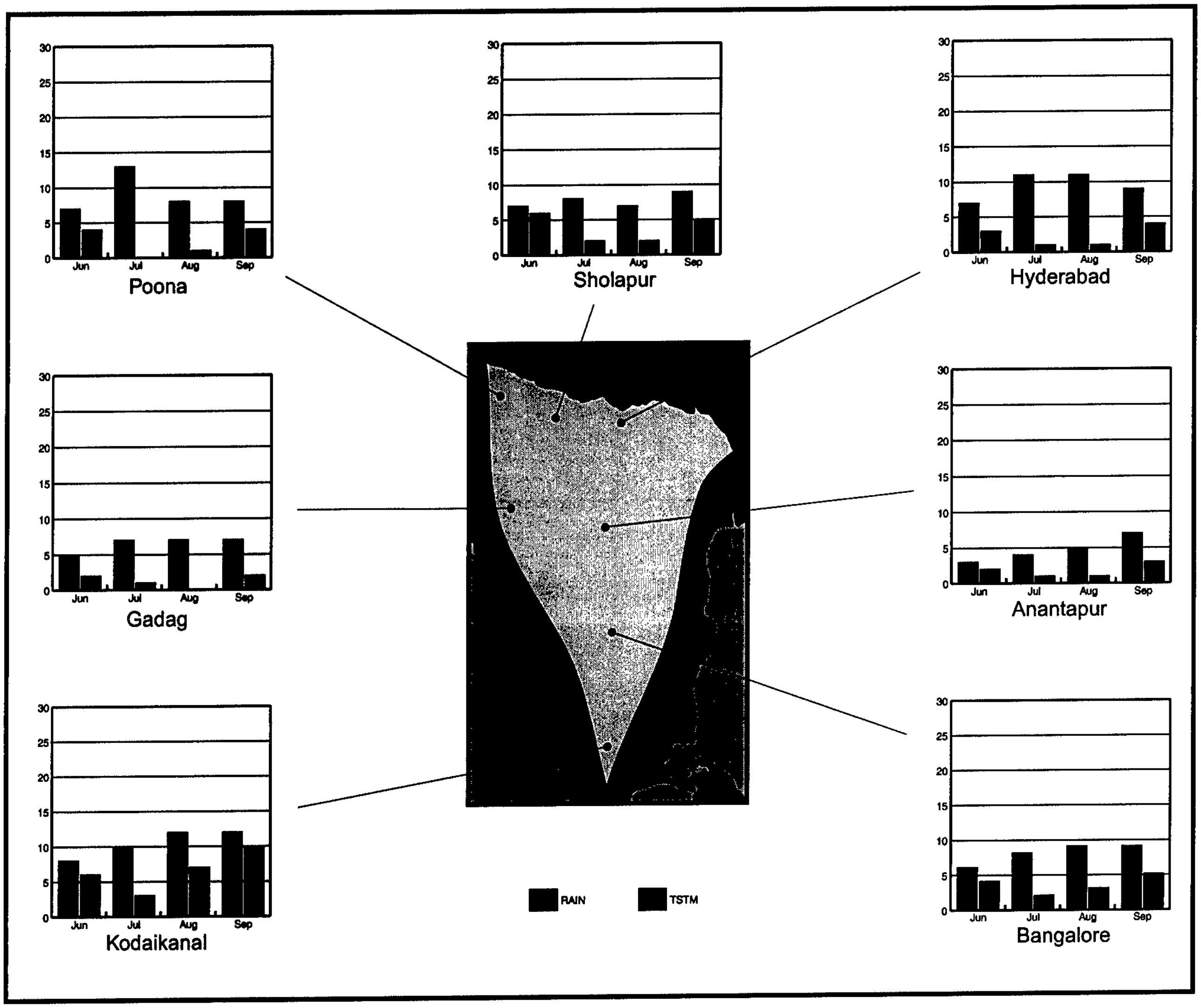


Figure 4-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Cloud cover and rain cool the air, and temperatures decrease from June into July then remain fairly constant through September. The relative humidity is the highest of the year, which makes the climate oppressive. Interior temperatures are warmer than areas close to the east coast and the northwestern corner lowlands are the warmest area in the region. Mean highs in June are 95° to 100°F (35° to 38°C) in the lowlands and 85° to 90°F (29° to 32°C) at higher elevations. From July through September, mean highs cool to 90° to 97°F (32° to 36°C) in the lowlands and 77° to 85°F (25° to 29°C) at higher elevations. In June, the lowlands have mean lows of 76° to 81°F (24° to 27°C), and the highlands have mean lows of 67° to 72°F (19° to 22°C). From July through September, they average 71° to 75°F (22° to 24°C) in the lowlands and 65° to 68°F (18° to 20°C) in the highlands. Temperatures cool moist adiabatically with elevation so the highest sites in the Cardamom Hills have mean highs of 62° to 65°F (17° to 18°C) and mean lows of 50° to 55°F (10° to 13°C) all season. The extreme highs are hottest in June, 109° to 114°F (43° to 46°C). In July through September, the extreme highs are lower, 100° to 105°F (38° to 41°C). The extreme lows are fairly consistent all season, 63° to 68°F (17° to 20°C). Highland extreme lows drop into the 55° to 58°F (13° to 14°C) range and the very high terrain drops into the 40° to 48°F (4° to 9°C) range. Figure 4-25 shows mean highs and Figure 4-26 shows mean lows for representative stations.

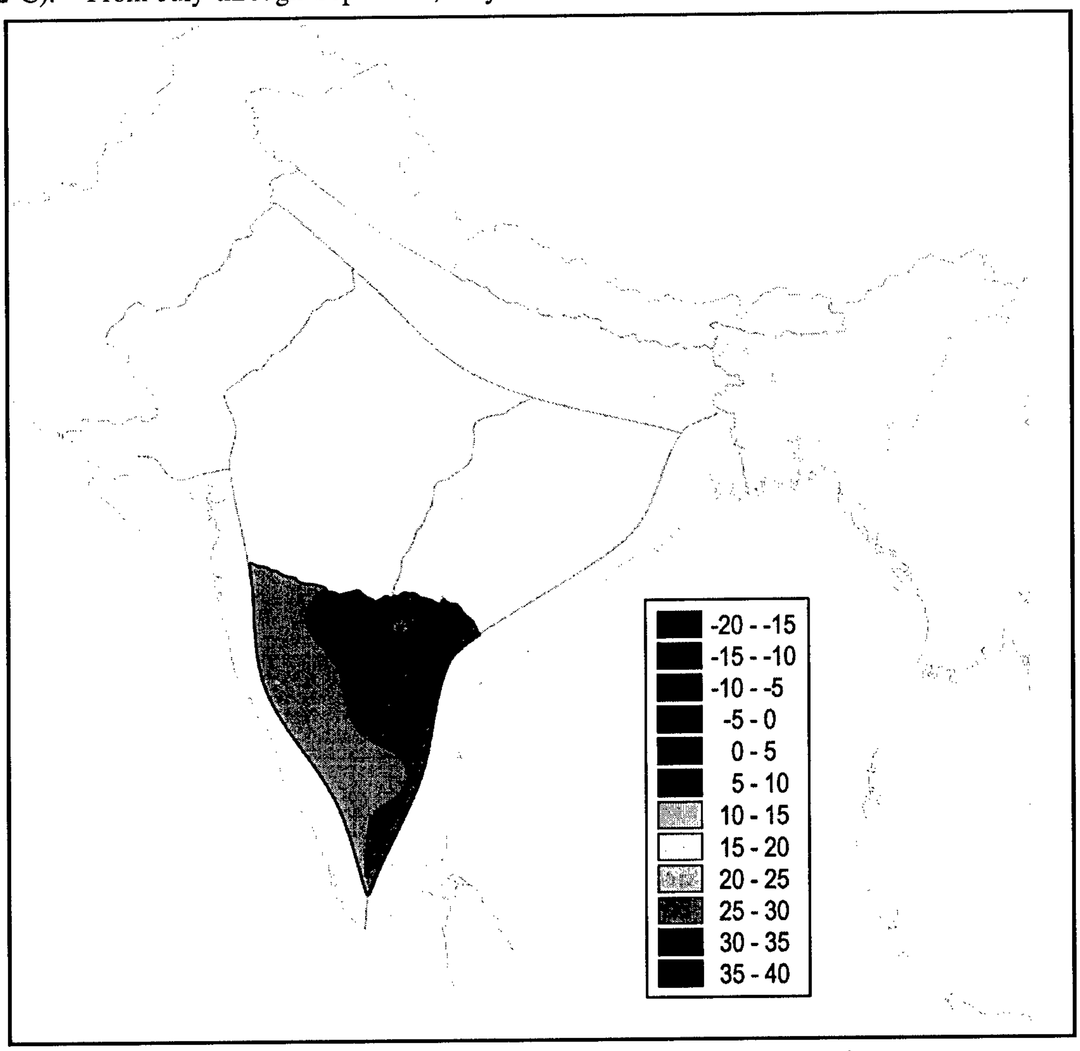


Figure 4-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other southwest monsoon months may be lower, especially at the beginning and ending of the season.

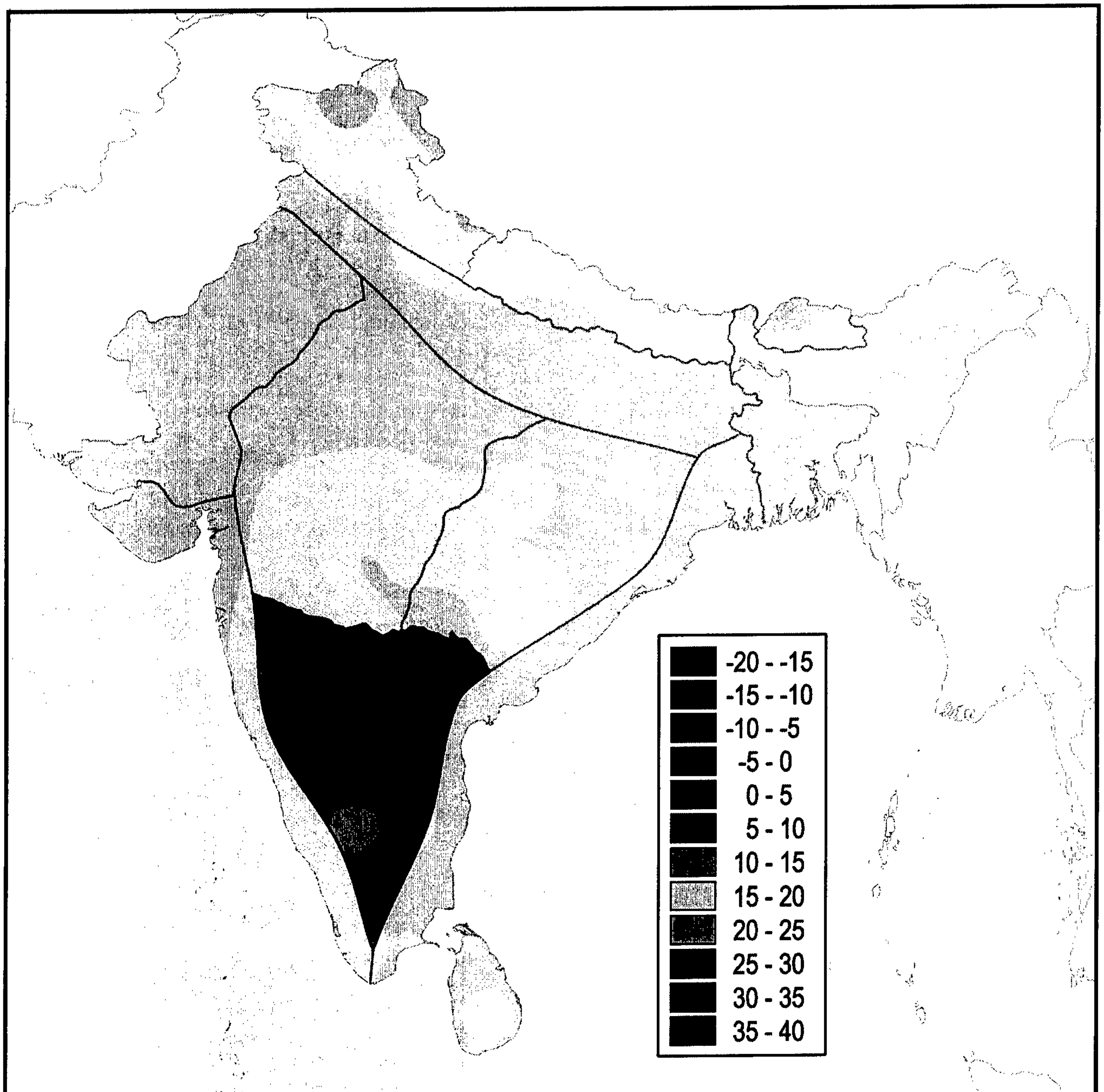


Figure 4-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other southwest monsoon months may be lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. The rains of the southwest monsoon season end. The equatorial trough (ET) begins its retreat southward as the thermal low over Asia fades away. The withdrawal of the southwest monsoon occurs more slowly than the onset. The progression southward takes 2 months, begins quickly then moves more slowly, and is usually orderly. It occurs first in the northernmost part of the region; the ET is south of the tip of the peninsula by late November or early December. Heavy rains accompany the ET as it moves through an area.

The equatorial westerlies, the Somali jet, and the tropical easterly jet all disappear. The deep band of easterlies also retreats southward in this phase. By the end of November, it will be largely south of the peninsula. The thermal Asiatic high begins to form now, and wind flow at all levels is relatively ambiguous as a result. Shear aloft is reduced in this transition season, so tropical cyclones have the best chance of developing and growing powerful. The Bay of Bengal is a favored breeding ground for tropical cyclones.

October and November are consistently more active tropical cyclone months than April and May. The Bay of Bengal water is warmest and storms reach maximum occurrence rates. These storms are not as powerful as open ocean storms, but they still carry heavy rains and strong winds to the coasts. The mean storm track in this season is spilt. One branch directs storms to a landfall in the northeastern coastal area. The other directs them to the southern end of the peninsula just north of Sri Lanka. The southern track is the more active track.

Sky Cover. Cloud cover decreases sharply to winter norms by November in most of the region. The southernmost tip of the peninsula retains more cloud cover since the southwest monsoon still has an impact as it is moving southward. During October, the average cloud cover is 40-50 percent in the north and 65-75 percent in the south. Generally, cloud cover is at the maximum in late morning through afternoon and at the minimum in the early morning. By November, cloud cover is down to 25-35 percent in most of the region but remains above 65 percent in the south. Figure 4-27 shows ceilings below 5,000 feet at representative stations.

October ceilings below 5,000 feet occur 10-15 percent of the time at all hours in the lowlands and in the rainshadow of the Western Ghats. Sheltered locations have them 5-9 percent of the time in the afternoons and under 5 percent of the time the rest of the day. In the lowlands, ceilings below 5,000 feet tend to occur most in late afternoon with cumulus, but the increase is small. At elevations above 3,000 feet (1,000 meters) in the Cardamom Hills, ceilings below 5,000 feet occur most in the afternoon through midnight. In the afternoons, they occur 75-85 percent of the time all season. By midnight, the rate drops to 65-75 percent of the time, and by morning, the rate is down to 40-50 percent of the time. At lower elevations above 1,500 feet (450 meters), they occur most in post-sunrise mornings to early afternoon, 35-45 percent of the time at most locations, but as much as 65 percent of the time in October in windward sites, such as Bangalore.

By late afternoon, ceilings below 5,000 feet occur 20-30 percent of the time and by midnight, 10-15 percent of the time. Windward, southern sites above 1,500 feet (450 meters) elevation tend to average slightly higher rates in the early morning hours, 25-35 percent of the time. By November, rates drop sharply at these elevations, even in the far south. They occur 20-30 percent of the time from sunrise to midday, 25-35 percent of the time in the afternoons and 10-20 percent of the time overnight. The southern sites have the most occurrences and the northern sites have the fewest.

Ceilings below 1,000 feet mainly occur at elevations above 1,500 feet (450 meters). Places below that have them only with rainshowers or thunderstorms. In the mornings, sites above 1,500 feet elevation have ceilings below 1,000 feet 20-25 percent of the time. By afternoon, they occur 5-10 percent of the time almost everywhere. Above 3,000 feet (1,000 meters) in the Cardamom Hills, morning ceilings below 1,000 feet occur 25-35 percent of the time in both October and November; in the afternoon, they occur 40-50 percent of the time in October and 65-75 percent of the time in November because the ET still lingers in the area.

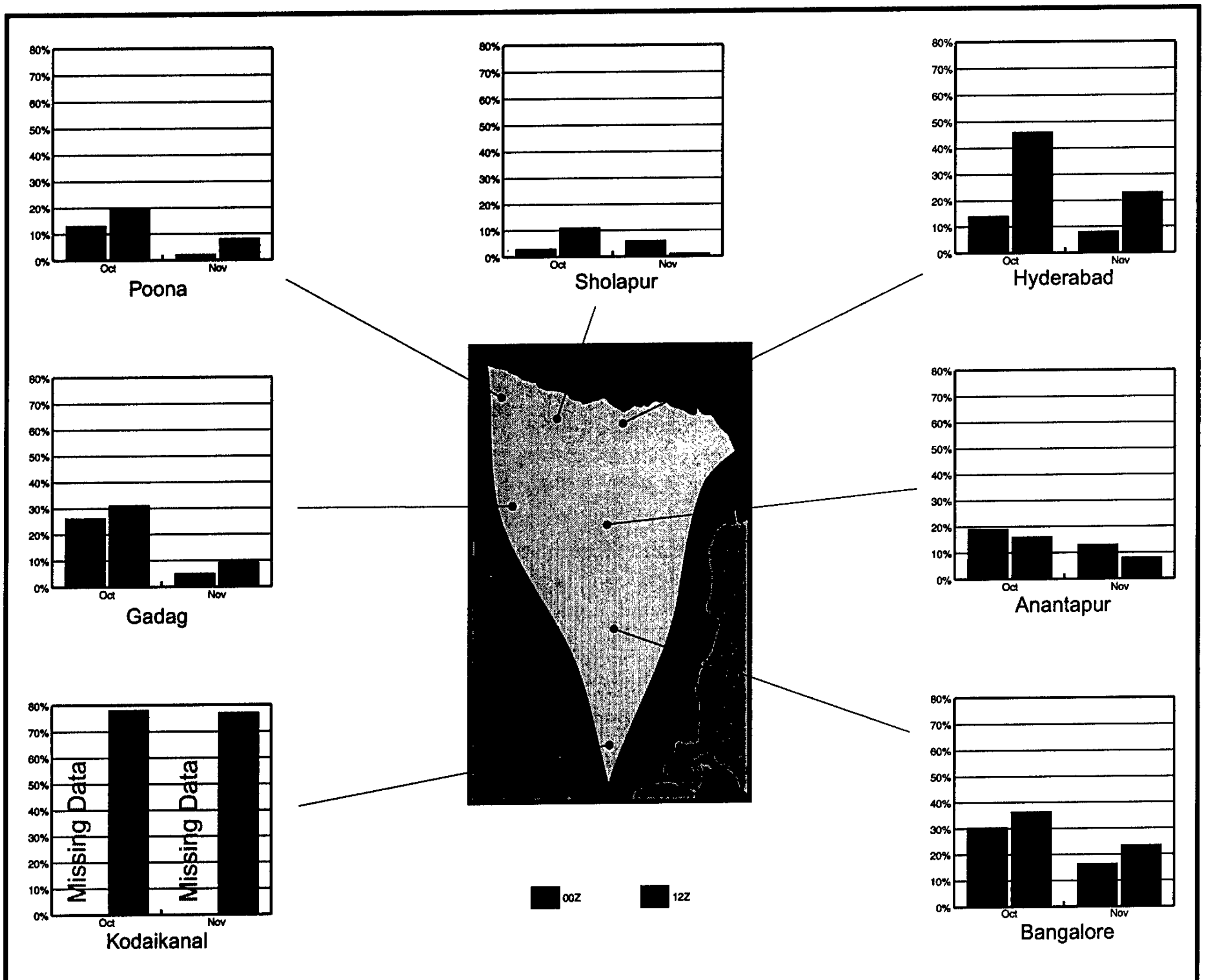


Figure 4-27. Post-Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility remains good through the whole season. Localized morning fog reduces visibility for a short time but quickly dissipates. Figure 4-28 shows visibility below 4,000 meters at representative stations.

Visibility below 2 1/2 miles (4,000 meters) occurs 10 percent of the mornings between 1,500 and 2,500 feet (450 and 750 meters) elevation and not at all the rest of the day. It occurs 15-25 percent of the time in the mornings at elevations above 2,500 feet (750 meters) and rarely the rest of the day. The exception is the high elevations in the Cardamom Hills, where afternoon visibility below 4,000 meters occurs 45-55 percent of the time. In the lowlands (below 1,500 feet or 450 meters elevation), visibility below 4,000 meters is rare; it occurs only with heavy precipitation.

Visibility below 1 1/4 miles (2,000 meters) occurs in the Cardamom Hills 15-25 percent of the time in the mornings and 40-50 percent of the time in the afternoons. Everywhere else, it briefly occurs with heavy rainshowers or thunderstorms.

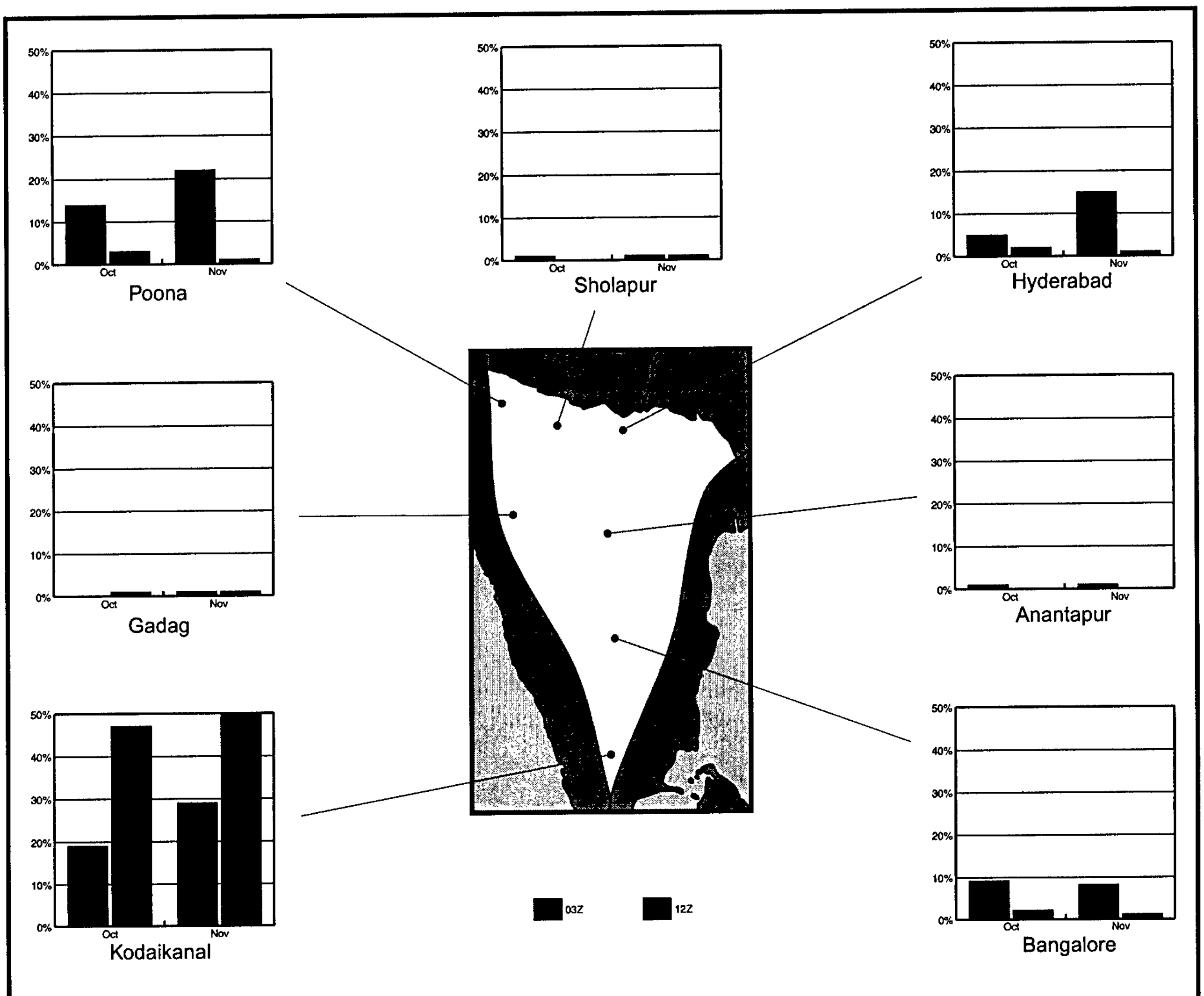


Figure 4-28. Post-Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Winds are more locally driven in this transition season. Night calms occur 50-75 percent of the time even at higher elevations. In sheltered Western Ghats valleys, they occur as much as 90-95 percent of the time. In all but the western highlands (roughly the western third of the region), winds are light and variable at 5 knots or less at night and generally from the northeast to east at 5-10 knots during the day. In the western highlands, west to southwest winds tend to dominate. Speeds are 5-10 knots at night and 10-20 knots during the day. At these higher elevations, the farther north a site is positioned, the lower the wind speeds it has. In the mountains, calms and light winds will allow drainage winds to flow at night and the direction will vary with position relative to terrain features. Figure 4-29 shows surface wind roses for representative stations.

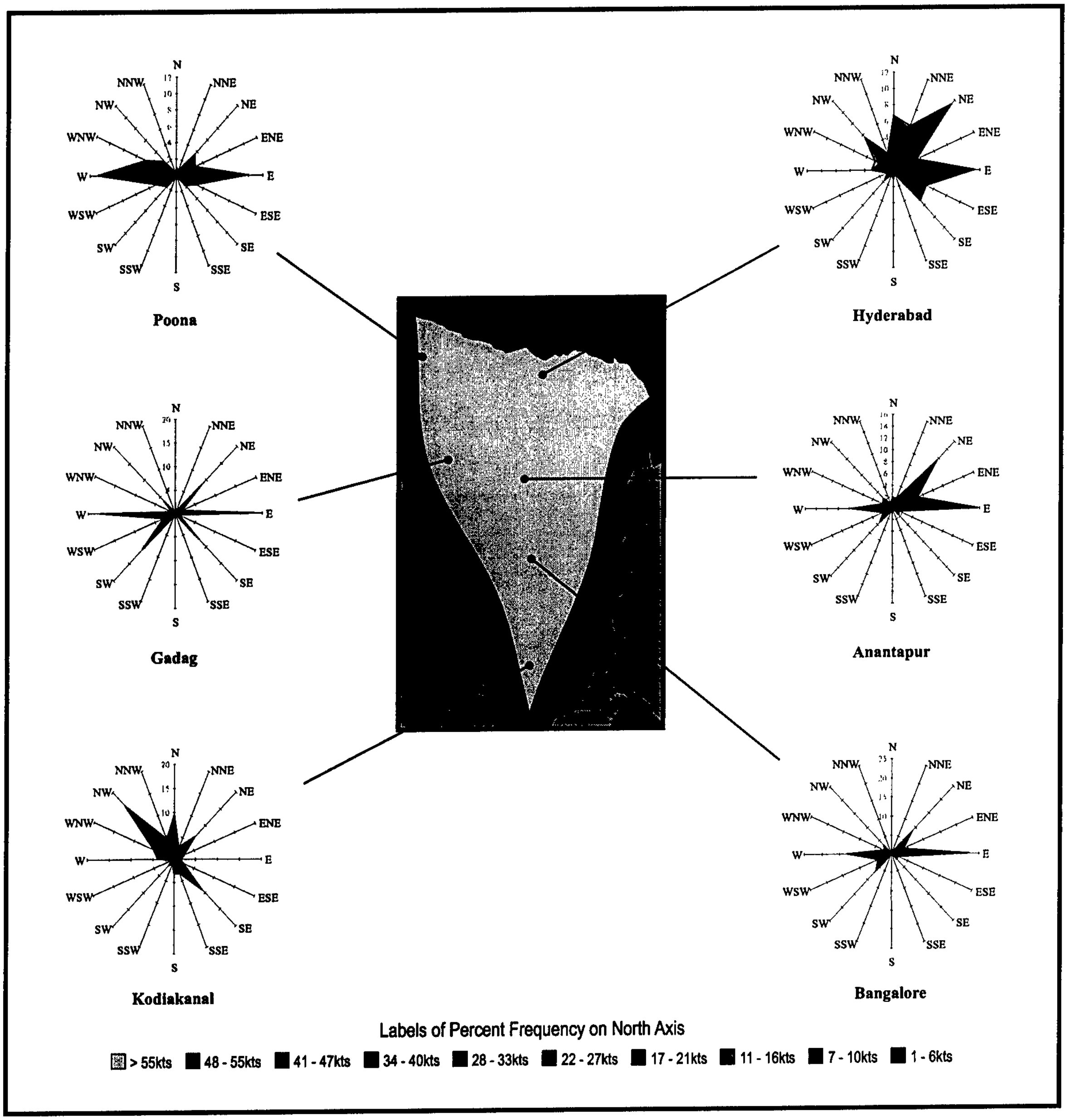


Figure 4-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The October winds at 850 mb are from west at 10 knots. In November, the 850 mb winds from the northeast-southeast at 10 knots. The 700 mb winds are easterly at 5-10 knots in both months. At 500 mb, the winds are from the east at 10-15 knots all season. At 300 mb, easterly winds at 10 knots in October give way to southwesterly winds at 10 knots in November. Figure 4-30 shows upper-level winds for Hyderabad.

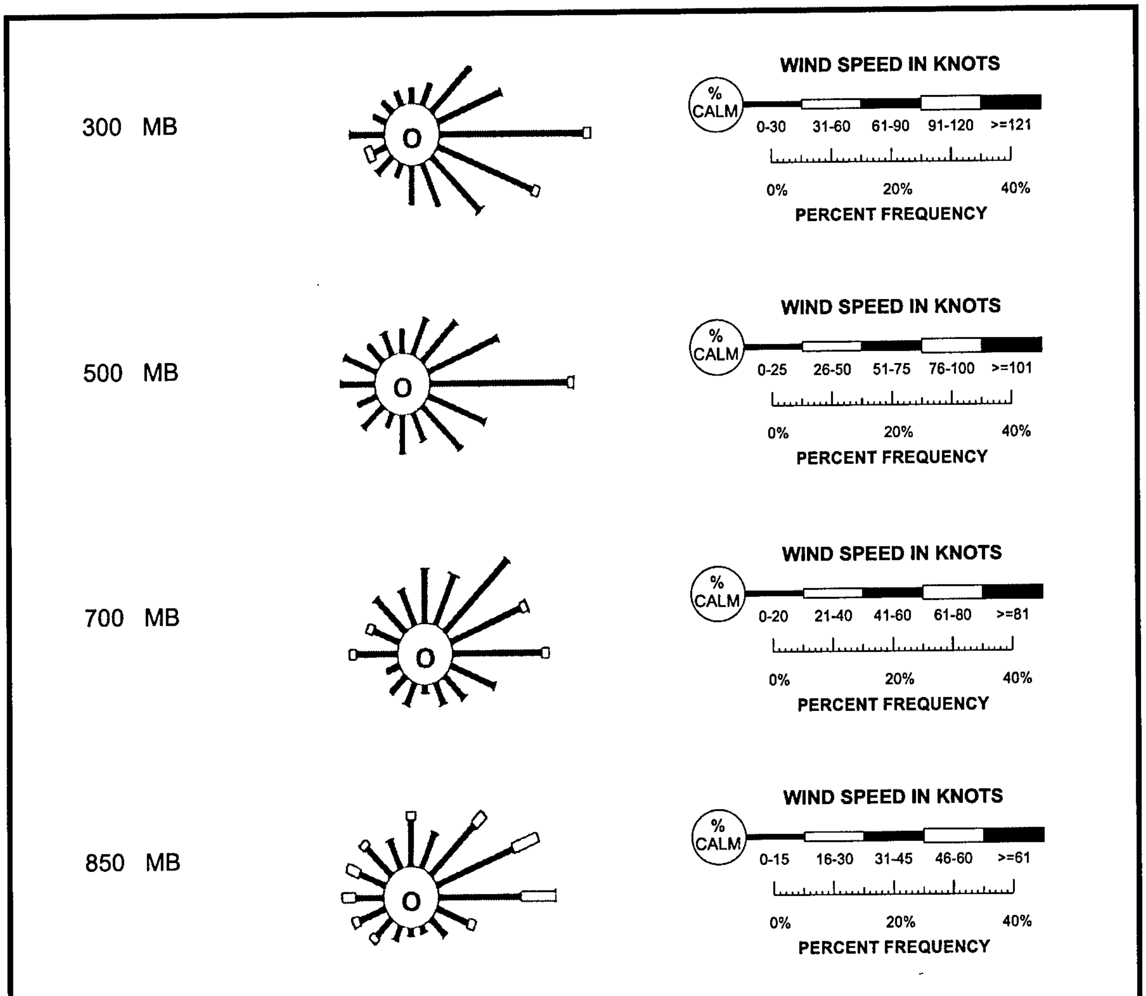


Figure 4-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Hyderabad.

Precipitation. The Cardamom Hills get the most rain of the year in this season as the ET lingers in the area. They average 10-12 inches (254-305 mm) of rain in both months. Elsewhere, rainfall decreases from October to November. In October, places close to the coast get 5-8 inches (127-203 mm) of rain (the most falls in the southeast corner of the region) and most interior places get only 2-5 inches (51-127 mm). The northwest corner of the region gets the least rain. By November, rain is light everywhere but in the southeast corner, usually 0.5-1 inch (13-25 mm) or less. The southeast corner averages 4-6 inches (102-152 mm). Rain falls 5-10 days in October and 1-7 days in November in most of the region. The fewest days are in the northwest corner and the most are in the southeast corner. The Cardamom Hills are the exception. Rain falls there on 16-18 days in October and 13-15 days in November.

September-October is the late-year thunderstorm maximum. At the southern tip of the peninsula, this period stretches into early November. In October, thunderstorms occur 2-4 days in the north third of the region, 4-6 days in the central third, and 7-9 days in the southern third. By November, these numbers drop to 1-2 days with thunderstorms just about everywhere, In the Cardamom Hills, October averages 12-15 days with thunderstorms in October and 6-8 days in November. Figure 4-31 shows precipitation amounts and Figure 4-32 shows rain and thunderstorm days at representative stations.

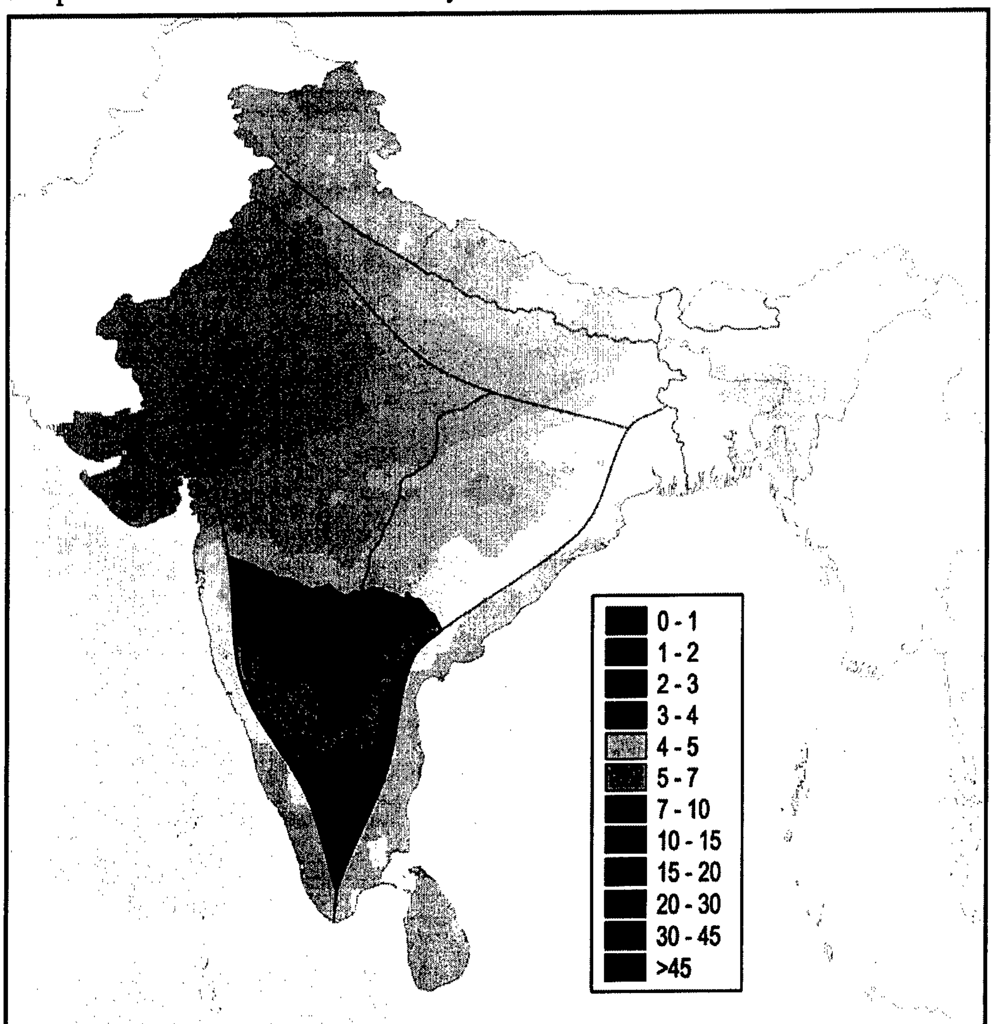


Figure 4-31. October Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

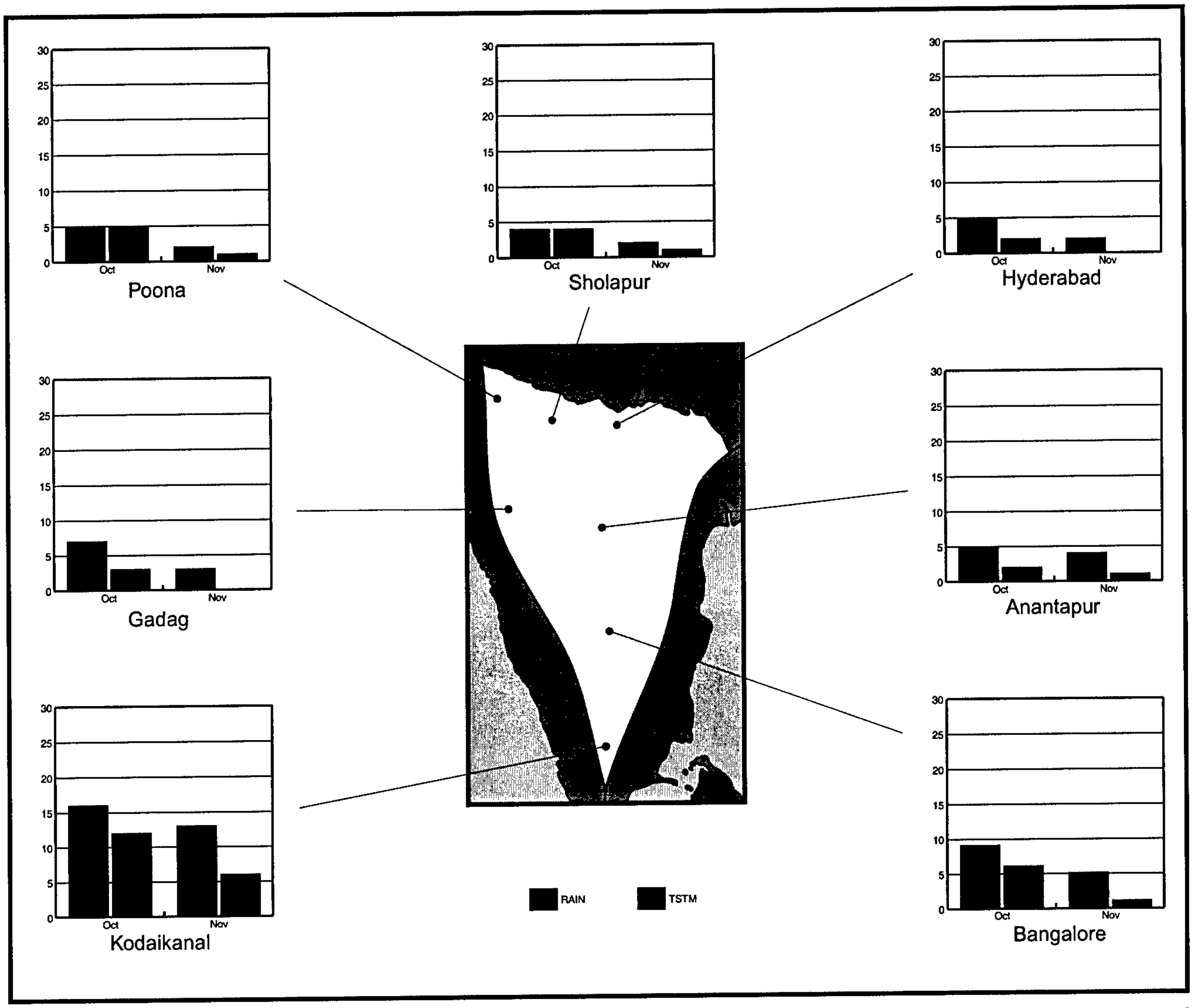


Figure 4-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. There is a slight temperature rise in October as both cloud cover and rainfall decrease. Temperatures decrease from October to November. In October, mean highs are 82° to 91°F (28° to 33°C) and mean lows are 66° to 75°F (19° to 24°C). By November, mean highs drop to 80° to 88°F (27° to 31°C) and mean lows are 58° to 69°F (14° to 21°C). The warmest highs and coolest lows are in the northwest corner of the region; the coolest highs and warmest lows are in the southeast corner. Extreme highs are 99° to 104°F (37° to 40°C) and extreme lows are 51° to 56°F (11° to 13°C). As temperatures cool moist adiabatically with elevation, mean highs in the Cardamom Hills are 60° to 65°F (16° to 18°C) and mean lows are 48° to 52°F (9° to 11°C) all season. Figure 4-33 shows mean highs and Figure 4-34 shows mean lows at representative stations.

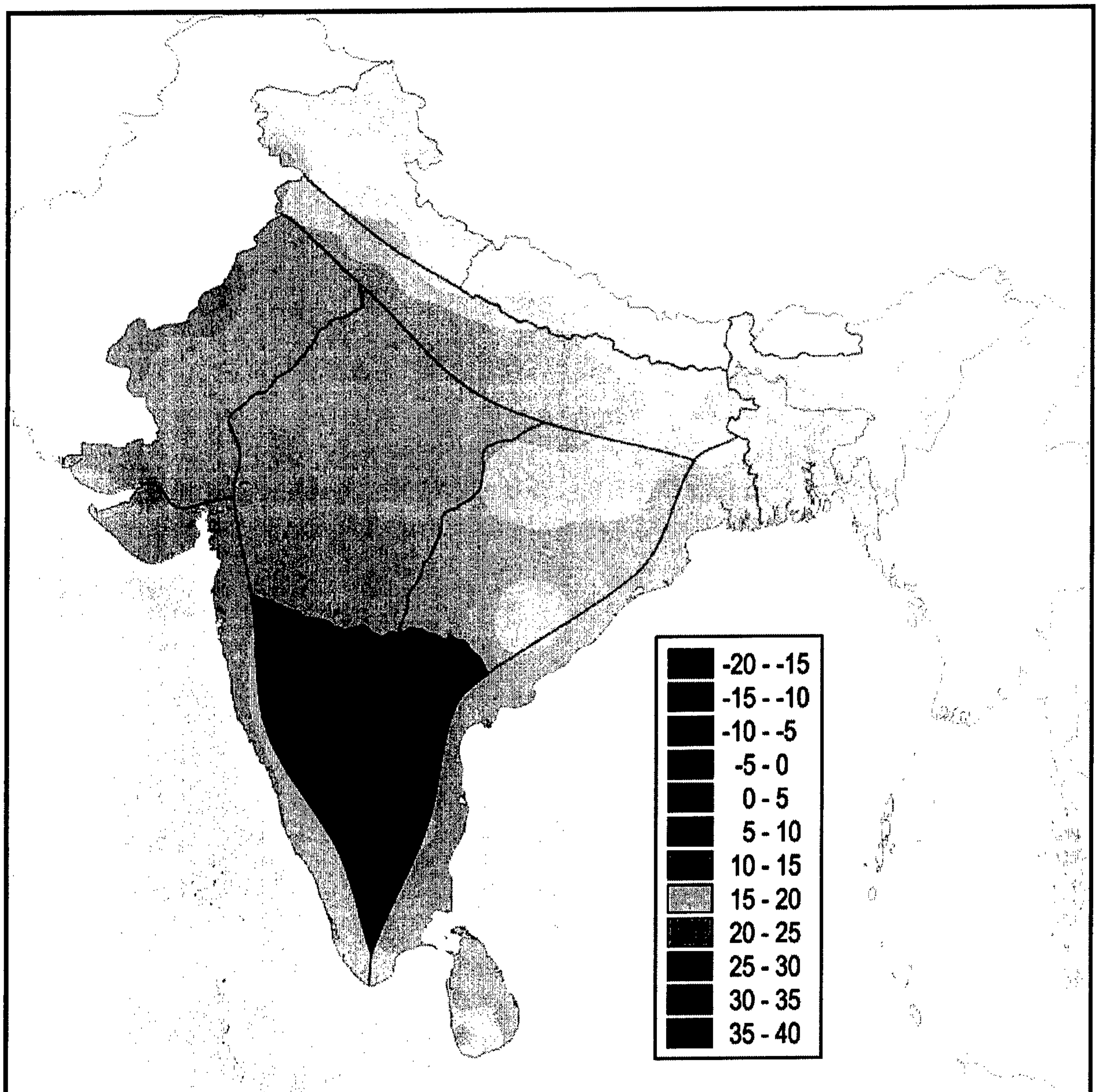


Figure 4-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in October. Daily high temperatures are often higher than the mean. Mean maximum temperatures during November may be lower.

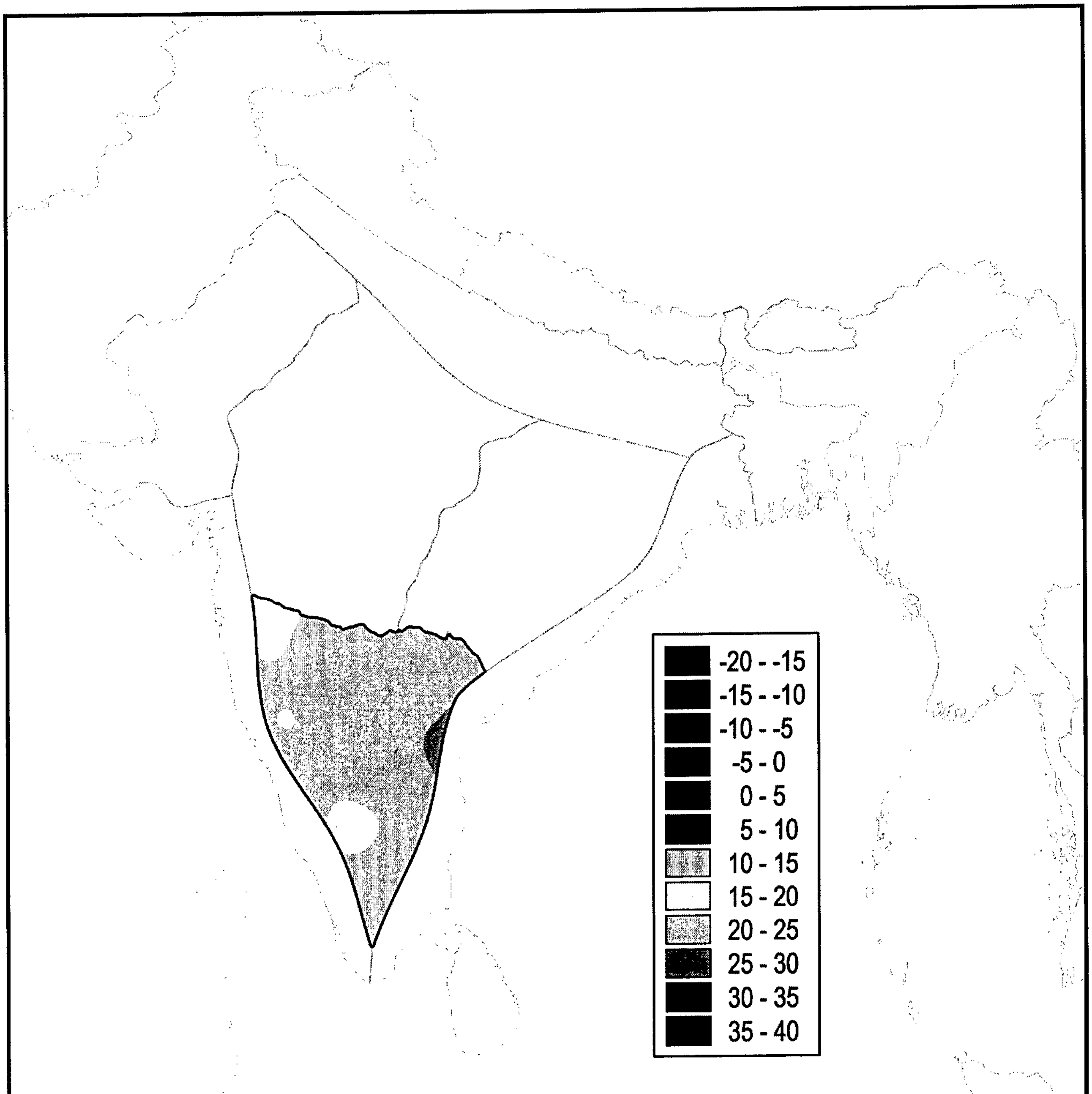


Figure 4-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in October. Daily low temperatures are often lower than the mean. Mean minimum temperatures during November may be lower.

Chapter 5

WESTERN COASTAL PLAIN

This chapter describes the geography, major climatic controls, special climatic features, and general weather by season for the Western Coastal Plain of India.

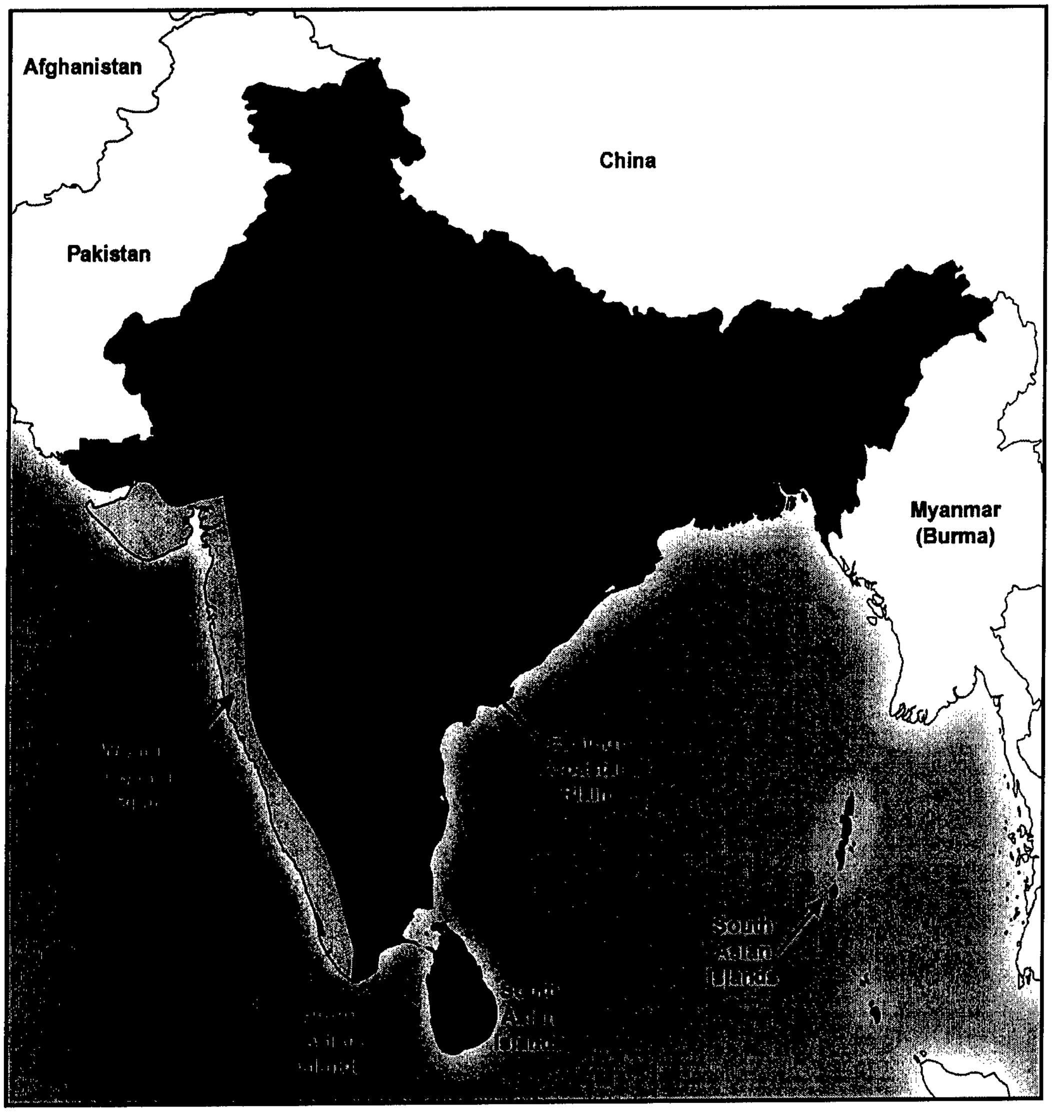


Figure 5-1. Western Coastal Plain. The area in yellow depicts the location of this zone.

List Of Topics

Topography

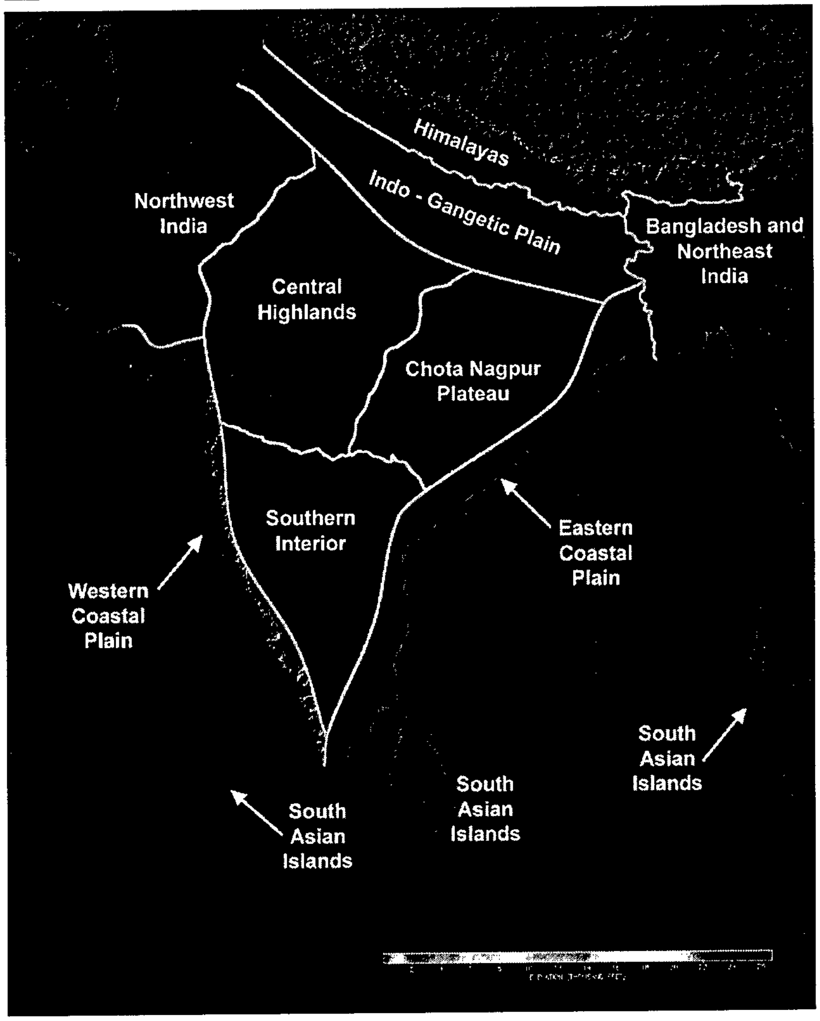


Figure 5-2a. Topographical Map of the Western Coastal Plain

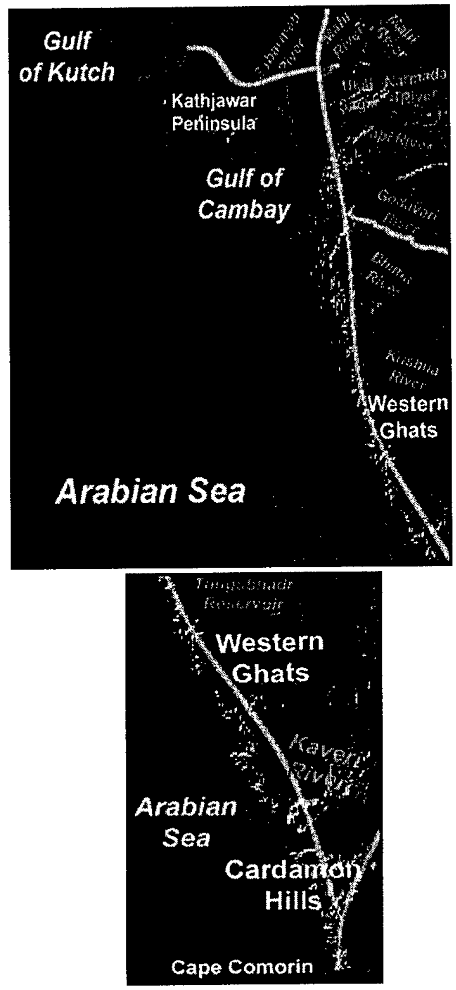


Figure 5-2b. Expanded View of Topography of the Western Coastal Plain.

Topography

Area. The Western Coastal Plain is a long, narrow strip of land between the Arabian Sea and the Western Ghat Mountains. The area begins at 22° N, 69° E on the south coast of the Gulf of Kutch. The north boundary extends 250 miles (400 km) east northeast. Near Ahmadabad, the boundary extends south for 1,025 miles (1,650 km) to Cape Comorin at the tip of the peninsula. The Western Ghats begin around 22° N, 62 miles (100 km) from the coast at the northern end. The range stretches for nearly 800 miles (1,300 km), almost to the southern tip of India. From Bombay to the southern end of the range, coastal plains are very narrow since the mountains are so close to the sea. Elevations are 3,000-5,000 feet (900-1,500 meters). The Gulf of Cambay, also called Khambhat, cuts north from the Arabian Sea into the land mass. The Kathiawar Peninsula, a wide, short peninsula, extends into the Arabian Sea. Most of it is low and flat. Maximum elevation in most of the area is 400-500 feet (120-150 meters.) Near the west tip, low hills reach 800-1,200 feet (240-365 meters). Another low range extends north-south in the center of the peninsula. These are also 800-1,200 feet, except in the south, where isolated tops reach 1,700 feet (500 meters). From the Kathiawar Peninsula area to the foothills of the Western Ghats, the land is low and flat, with elevations generally less than 500 feet (150 meters).

Major Water Bodies. The west coast of India faces the Arabian Sea. The Gulf of Kutch is an inlet of the Arabian Sea at the northwest coast of the Kathiawar Peninsula. Another inlet, the Gulf of Cambay, is at the southeast coast of the peninsula.

Rivers, Lakes, and Drainage Basins. Three major rivers rise in the mountains of north central India and flow through the northwestern coastal plains. The Narmada flows 800 miles (1,285 km) to the Gulf of Cambay. The Tapi, 80 miles (130 km) south parallels the Narmada and discharges into the Gulf of Cambay. The Tapi is 436 miles (700 km) long. Several minor, short rivers also flow from the central mountains into the Gulf of Cambay. The Western Ghats are drained by many small rivers and streams that flow down the west flanks to the Arabian Sea. The eastern flanks of the Western Ghats are drained by several major rivers that flow down the slopes of the mountains toward the east.

There are numerous lakes, some quite large, in enclosed valleys in the Western Ghats. Many are manmade. The Ukal Sagar (reservoir) is at 21°30' N, 73°35' E. The reservoir is nearly 40 miles (64 km) long and as much as 10 miles (16 km) wide at an elevation of 414 feet (126 meters).

Major Climatic Controls

South Indian Ocean (Mascarene) High. This year-round high is strongest during the southwest monsoon. As it strengthens in April and May, its warm, moist outflow helps push the equatorial trough (ET) to the north. It is a key driver of the southwest monsoon over India.

Asiatic High. This intensely cold high develops over Asia and dominates the weather over the continent from November to April. The great height of the Himalayas blocks movement of air into India. Some of the outflow arrives from the northwest over the mountains of Pakistan, and some from the northeast after a long over-water trajectory. This is a key driver of the northeast monsoon. With the Australian low, it sends the ET south of India. The Asiatic high fosters the development of a leeside trough at the southern foot of the Himalayas, which provides a track for westerly disturbances across northern India.

North Pacific High. This high is farthest west and north during the southwest monsoon season. During the winter, when it is farther south, it helps keep the ET south of India, which shuts off the moist air from the southwest.

Australian High. This high develops during the southwest monsoon. As it gains strength, it works with the Asiatic low to send the ET northward, which opens the way for the southwest monsoon to move into India. It also helps strengthen the tropical easterly jet that enhances convective activity in the Bay of Bengal.

Australian Low. This is a thermal low that develops over Australia during the Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

Asiatic (Pakistani Heat) Low. This thermal low develops during the southwest monsoon. It anchors the east end of a trough that extends west to the Sahara Desert. The pressure gradient between this low and the belt of high pressure in the Southern Hemisphere contributes to the strong flow of warm, moist air over India during the southwest monsoon.

Tibetan Anticyclone. This system develops above the thermal heat low that forms on the Tibetan plateau during the southwest monsoon season. Outflow from the southern periphery of the system helps strengthen cyclonic storms that develop in the India-Myanmar trough over the northern Bay of Bengal by providing upper-level outflow.

Indian High. This thermal high occasionally sets up over the Indian peninsula during the winter and hot season. It forms during a cold outbreak and stabilizes the weather over the whole area, bringing clear-to-scattered skies, generally good visibility, and light winds. Although always weak, when the high is relatively strong, it tends to block low pressure systems from the track across the southern foot of the Himalayas by displacing the lee-side trough that is typically in place. When the high is weakest, it tends to intensify the lee-side trough. This provides a pipeline for lows out of Europe that ride the subtropical jet to move rapidly across northern India.

India-Myanmar Trough. This trough develops near 85° E during the southwest monsoon. It strengthens the tropical easterly jet and is a preferred area for monsoon depression development. The Tibetan anticyclone provides outflow for tropical cyclones, monsoon depressions, and other disturbances that develop along this trough.

Major Climatic Controls

Equatorial Trough (ET). This convergence zone, also called the monsoon trough in this region, marks the boundary between the dry, stable air of the northeast monsoon and the moist, unstable air of the southwest monsoon. When it is farthest south, the warm, moist air from the southwest is blocked, and the area is relatively dry. When it moves north, southwest airflow moves with it.

Tropical Easterly Jet. This jet develops at the 300-200-mb level during the southwest monsoon. It is created by outflow from the southern edges of the Tibetan anticyclone and the permanent Pacific/Indian Ocean highs. It provides outflow for convective activity under the ET.

Somali Jet. Also known as the East African low-level jet, it exists during the southwest monsoon and is a significant transport for warm, moist air from the Southern Hemisphere. It is a key element in the creation of the equatorial westerlies that dominate the southwest monsoon season.

Subtropical Jet. During the winter and hot seasons, this jet is south of the Himalayas at 35,000-40,000 feet. Core speeds are near 75 knots. It helps steer western disturbances across extreme northern India along the leeside trough that develops at the foot of the Himalayas.

Special Climatic Controls

Monsoon Depressions. These systems account for much of the rain of the southwest monsoon. Their prime breeding grounds are over the warm waters of the Bay of Bengal and, less often, the Arabian Sea. They are most common in October and November but occur at any time during the southwest monsoon. The heaviest rain falls in the southwest sector of the storm. Many track northwest across India from the Bay of Bengal, but some move due west across the peninsula. As they cross, they bring heavy, widespread rain, thunderstorms, and thick, low clouds.

Western Disturbances. These are migratory lows that move east along the southern periphery of the Himalayas along the leeside trough that develops there. They are most frequent from December to April. A warm front often proceeds the low and a weak cold front follows. Thunderstorms may occur with cold frontal passage. The lows bring extensive cloud layers and moderate to heavy precipitation to northern India. They occur on average 5-7 time each month during December-April.

Mid-Tropospheric Cyclones. These develop during the southwest monsoon near the 600 mb level. They occur most frequently in the northeastern Arabian Sea, and are major producers of rain on the Western Coastal Plain of India. A weak trough offshore of the northwest coast is often the only indication of a disturbance. The cyclones produce wide-spread layered clouds, imbedded thunderstorms, and heavy precipitation (8 inches or 200 mm in 24 hours is not uncommon). The systems usually last 9-10 days and are essentially stationary during their life cycle.

Tropical Cyclones. Tropical cyclones move into the Arabian Sea on average once or twice per year. Cyclones are most common during October and November when the water is warmest. The second most active period is at the end of June. Strong storms in the Bay of Bengal produce widespread cloudiness and torrential rainfall over most of the peninsula, including the western coastal plain. Storms in the Arabian Sea usually move west or northwest, away from the coast. They produce widespread cloudiness and very heavy rains. Storms in the Arabian Sea have, very rarely, turned east to affect the northwest coast of India. They gain strength as they cross the warm waters of the sea, can cause devastating floods on the coastal plain, and bring destructive winds.

Sea/Land Breezes. These local winds are common on the coast, especially during the winter and hot seasons when cloudiness is at a minimum. The breeze usually reaches no more than 20 miles (30 km) inland. In the north, the Western Ghats are 62 miles (100 km) from the coast, but from Bombay south, they are much closer to the coast. The sea breeze reaches the mountains in the south, and orographic lifting of the warm, moist air from the Arabian Sea produces cloudiness on the western slopes of the mountains. The land breeze is enhanced during the winter and hot seasons by the weak northeast flow over the area and slope wind from the mountains close to the coast. The air from the land is cooler than the air over the sea. Stratus, stratocumulus, or cumulus clouds develop a few miles offshore. In the southwest monsoon season, winds are steadily onshore at all hours. The monsoon flow is enhanced by a sea breeze during the day. The land breeze does not occur during this season because the monsoon flow overrides it.

Hazards for All Seasons

Turbulence. Under the clear to scattered skies of winter and the hot season, turbulence caused by intense surface heating may extend up to 10,000 feet. The turbulence is usually light-moderate but can reach the severe category. Winds blowing across the peaks of the Western Ghats may cause mechanical turbulence over and up to 50 miles (80 km) downwind. The turbulence is usually moderate but may reach the severe category. Obscured by the heavy clouds of the southwest monsoon, rotor clouds that indicate this turbulence will not be visible. Moderate to severe turbulence will be encountered in the vicinity of the subtropical jet at 35,000-40,000 feet during the winter and hot seasons. During the southwest monsoon, moderate to severe turbulence occurs near the tropical easterly jet at 40,000-45,000 feet.

Icing. The mean height of the freezing level is 16,000-18,000 feet year round over India. The mean height of the -20° C isotherm is 26,000-28,000 feet all year. Above and below these levels, icing does not usually occur. During the winter and hot season, there are very few clouds so there is little threat from icing. Heavy, dense clouds blanket the area during the southwest monsoon. In clouds, moderate to severe icing could occur between 16,000-28,000 feet.

Thunderstorms. Thunderstorms are frequent and often violent during the southwest monsoon. The most active periods are May-June and September-October, during the ET advance and retreat. During the winter and early hot season, thunderstorms develop along the cold fronts with western disturbances. Thunderstorms may produce torrential rain, strong wind gusts, violent up and down drafts, turbulence, icing, lightning, and in-cloud hail. Hail seldom reaches the ground; if it does it is usually small, soft, and causes little damage.

Flooding. Incredible amounts of rain fall in a very short period of time during the southwest monsoon. Streams and rivers overflow their banks and fill the valleys. Flash floods occur with little or no warning.

Temperature. The temperature and humidity are high all year. These conditions are debilitating and often very dangerous. Dehydration, heat stroke, and sun stroke are always a hazard. The hot season (March-May) is especially dangerous. The temperature is often 100° F (38° C) or hotter. Locations on and near the Kathiawar Peninsula are the hottest and most hazardous.

Tropical Cyclones. Bay of Bengal storms occasionally move across peninsular India and bring heavy, layered clouds and torrential rains to the west coast. High winds and flash floods can occur. The storms in the Arabian Sea usually move northwest or west, away from the coast. They will bring layered clouds and heavy rains as they pass. If a storm moves east and impacts the coast, strong winds, high tides, and flooding can be devastating.

Dust Storms. Dust storms are common in northern India during the hot season. During the winter and hot seasons, vegetation dries and leaves the soil bare. Strong convective currents created by intense surface heating lift the dry, barren soil as high as 10,000 feet. Migratory lows moving across northern India from the west carry the dust to 25,000 feet or higher. The dust gives a red-yellow glare to the sunlight. The air clears when monsoon rains begin.

Winter

General Weather. The area has light, northerly flow that originates in the Asiatic high far to the north. The height and vast expanse of the Himalayas keep the coldest air from reaching India because the outflow warms before it reaches South Asia. The North Pacific high, at its most southerly position, and the thermal low over Australia combine with the Asiatic high to keep the equatorial trough (ET) well south of India during winter. The area gets little cloudiness or rain most of the season. Migratory lows driven by the subtropical jet cross northern India. Thunderstorms may accompany the cold front that follows the low. These lows bring increased clouds to the northern west coast. The ET moves erratically as the strength of the dominating highs varies. At times, it is still across southern India in December. The southern tip of India experiences cloudy skies, rain, and thunderstorms until the ET moves far south of the peninsula, and the entire west coast area is under weak northerly flow. of the peninsula, and the entire west coast area is under weak northerly flow.

Sky Cover. The area experiences sunny skies most of the winter. The sky is mostly scattered or clear. Diurnal variations are small. The ceiling is less than 10,000 feet 5 percent or less of the time in the north and less than 15 percent of the time farther south. Cochin, in the middle of a long, swampy drainage plain on the southwest coast experiences more cloudiness. The ceiling is less than 10,000 feet up to 20 percent of the time. Ceilings less than 3,000 are uncommon in the area as seen in Figure 5-3. They occur only 7-8 percent of the time in the south, and less than 5 percent of the time in the north. Lower ceilings are extremely rare. Low stratus ceilings may form during the early morning hours in low, marshy areas and in large river valleys. The clouds usually dissipate shortly after sunrise. Migratory lows that move across northern India bring an increase in cloudiness to the northern part of the area as they move east.

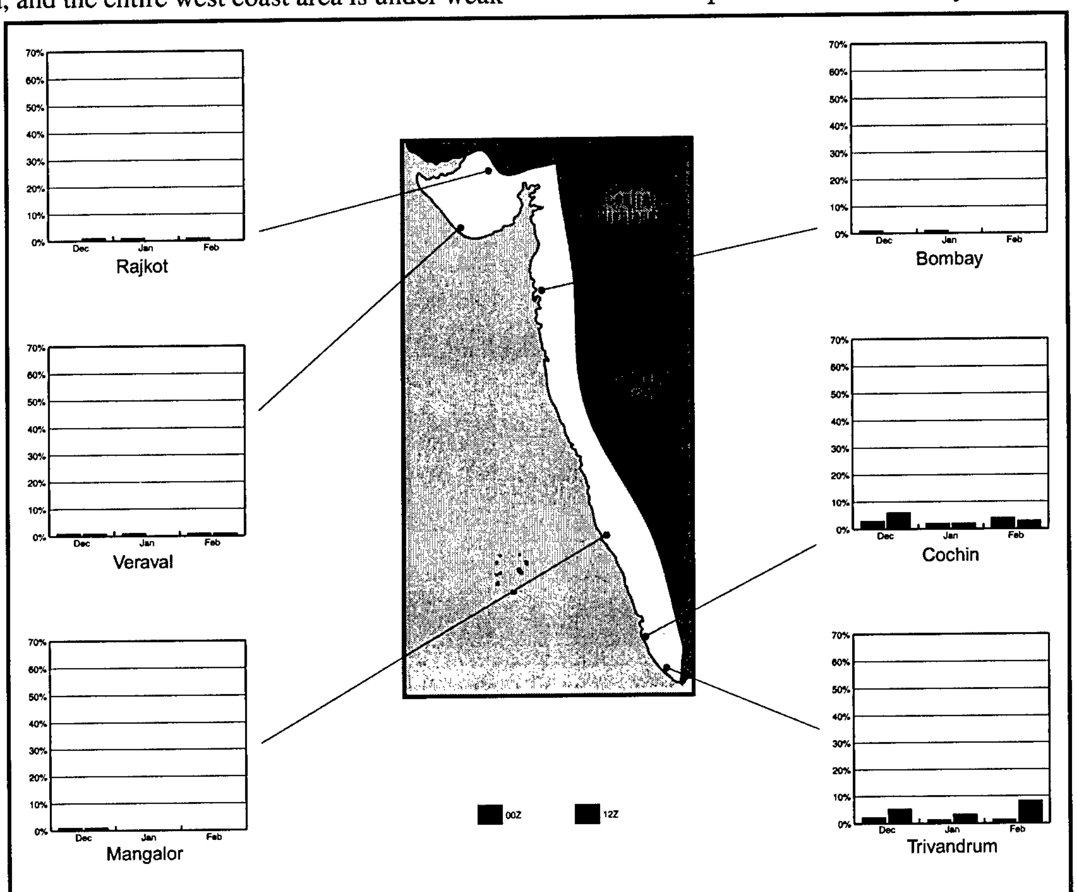


Figure 5-3. Winter Season Percent Frequency of Ceilings below 3,000 Feet. The graphs show a monthly breakdown of the percent frequency of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. Visibility is generally unrestricted during the winter season, although it is less than 6 miles (9,000 meters) at most locations at midnight and in the early morning. The visibility is below 6 miles (9,000 meters) up to 75 percent of the time at some stations on the Kathiawar Peninsula. Bombay, a large city, experiences this visibility up to 80 percent of the time at 0800L. Visibility is below 6 miles at stations farther south less often, only up to 15 percent of the time at 0800L. Trivandrum, at the tip of the Indian peninsula, experiences visibility less than 6 miles as often as 65 percent of the time at 0800L. At 1700L, the visibility is less than 6 miles 10-15 percent of the time at most stations. Cochin, in a low, swampy plain, experiences it 35-40 percent of the time.

Ground fog in low, swampy areas and river valleys, industrial pollution, and smoke often reduce the visibility to 4-5 miles (6,000-8,000 meters). Visibility improves after sunrise and usually remains good during the day.

Figure 5-4 shows that visibility less than 2 1/2 miles (4,000 meters) is not common except in a few locations. Cochin reports this condition up to 35 percent of the time during the day. Rajkot, on the Kathiawar Peninsula, gets it 30-40 percent of the time at 0800L and not at all the rest of the day. The visibility is rarely below 11/4 miles (2,000 meters) anywhere except on the Kathiawar Peninsula, where it occurs up to 10 percent of the time.

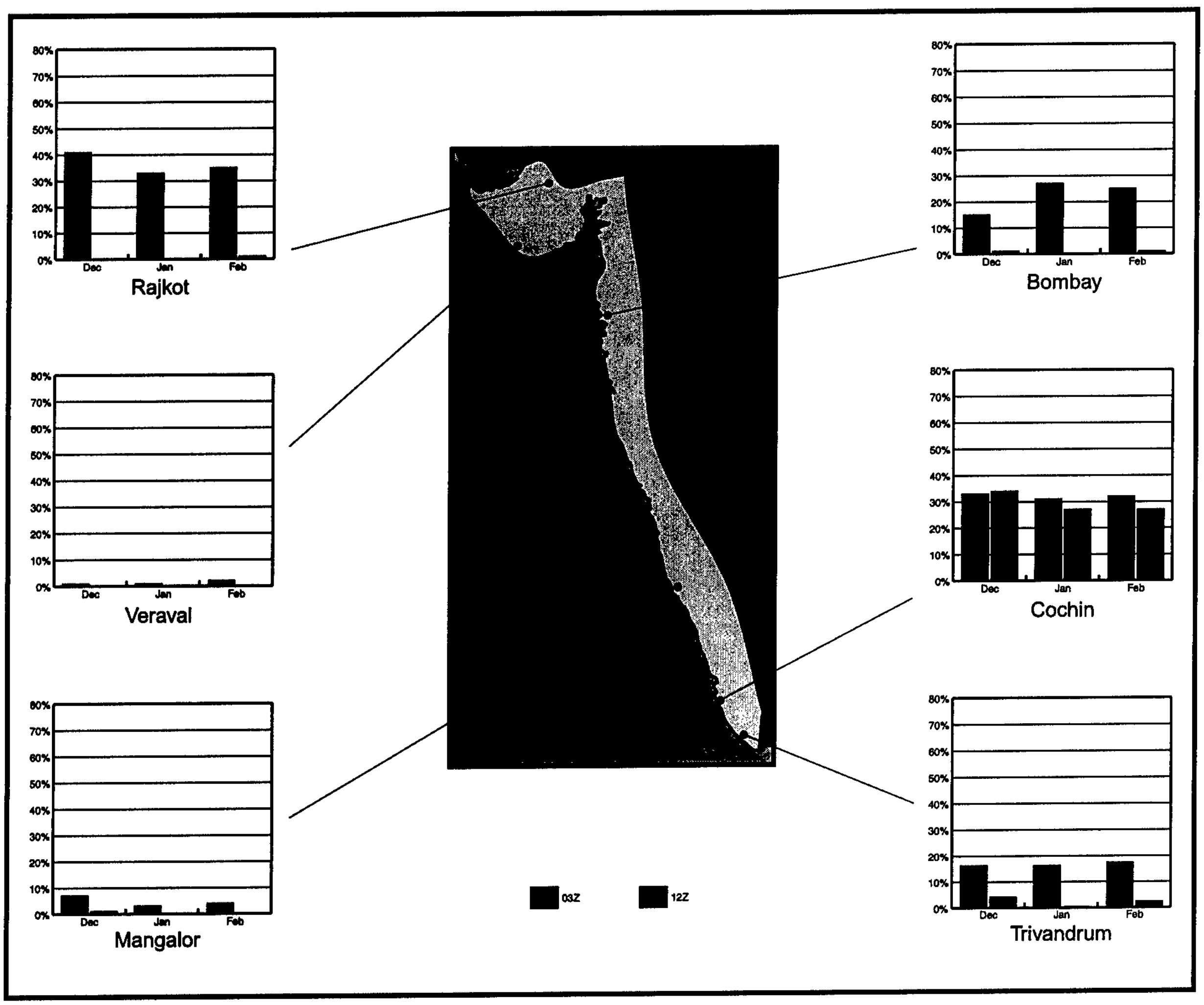


Figure 5-4. Winter Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent frequency of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. India is under light, northerly flow. West of the Western Ghats, the synoptic wind flow is so light the sea breeze often overwhelms northerly flow. The wind roses in Figure 5-5 depict "all hours" winds. At many stations, the winds are controlled by local land/sea breezes. Mangalore shows about equal frequencies of east and west winds. At 0500L, east winds at less than 8 knots occur nearly 40 percent of the time. At 1700L, west winds at 8-12 knots occur 40 percent of the time. Similar wind patterns occur along the whole west coast. In the north, the winds are generally from the north at 8 knots or less all day.

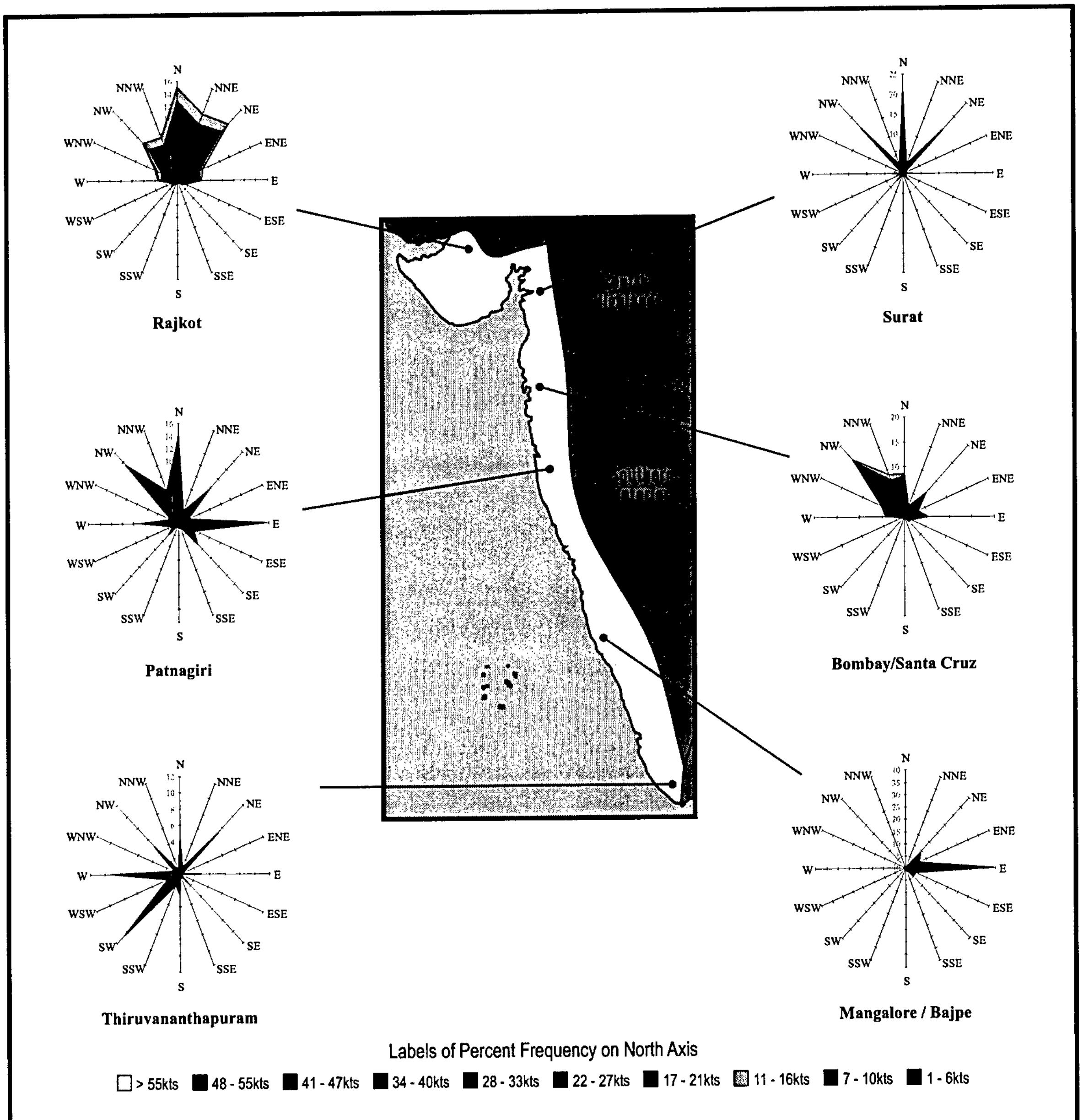


Figure 5-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Wind directions vary with latitude as well as height. Northeast and east winds prevail in the southern part of the area up to 500 mb. Farther north, winds are easterly up to 10,000 feet, then westerly flow begins to prevail. From Bombay north, southwest winds prevail to 700 mb. At 500 mb and 300 mb west winds are predominant. Wind speeds are 60-90 knots at 300 mb, and at times, over 100 knots. This reflects the southern periphery of the subtropical jet; its core is near 200 mb over the southern edge of the Himalayas during winter.

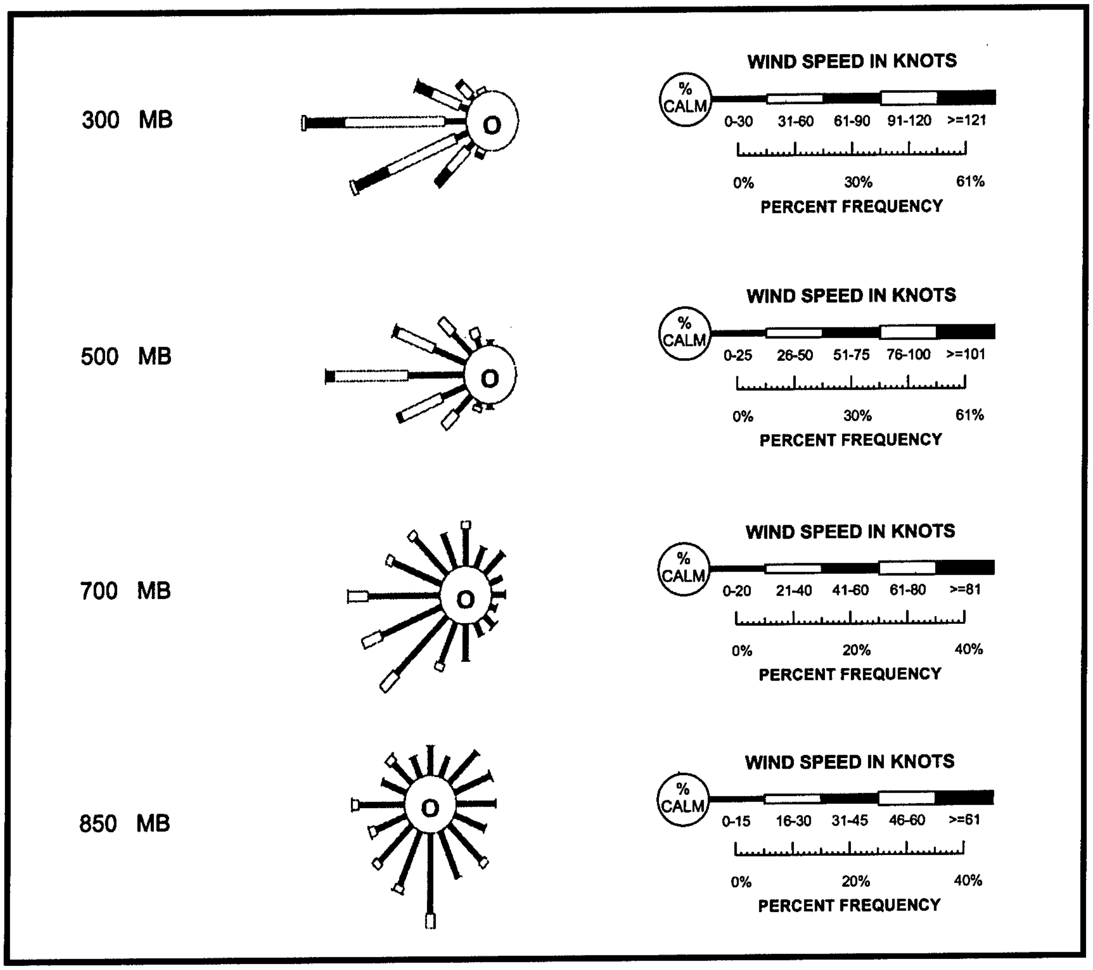


Figure 5-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Bombay.

Precipitation. It is very dry; rain falls on only 1 day per month along most of the west coast. On the south coast, rain falls 2 or 3 days per month. At Trivandrum, at the southern tip of India, rain falls up to 8 days in December, but only 3 days in January and February. Except for the southern west coast, only 0.1 inch (2.5 mm) or less of rain falls each month during the season. At Trivandrum 2.6 inches (66 mm) of rain falls in December, 1 inch (25 mm) in January, and 0.9 inch (23 mm) in February. Thunderstorms are rare. One occurs at most stations during the season, except Trivandrum, where 2-4 occur each month. The heavier precipitation and thunderstorms in the southern areas are due to the erratic retreat of the ET. Figures 5-7 and 5-8 show January mean precipitation amounts and seasonal precipitation and thunderstorm days, respectively.

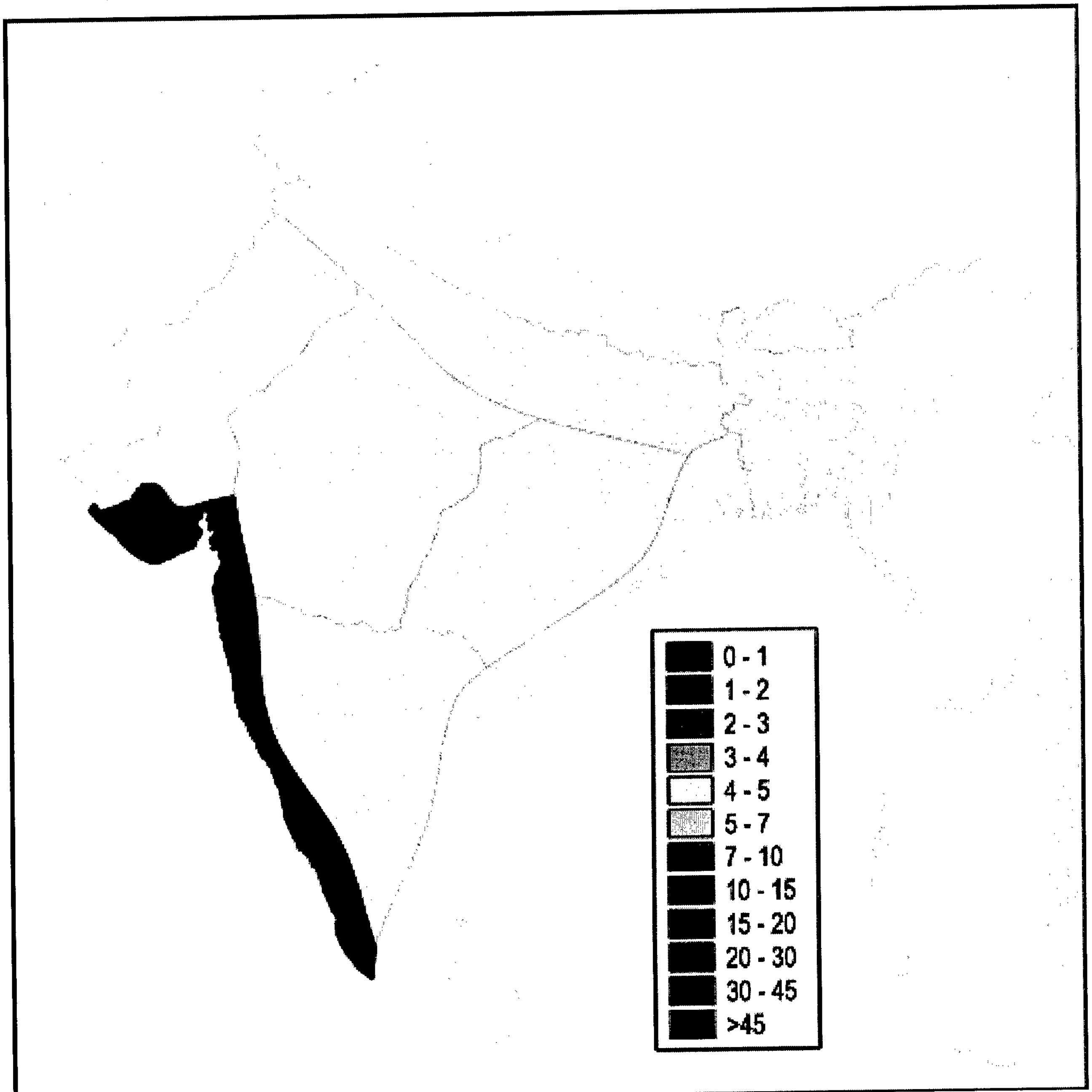


Figure 5-7. January Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

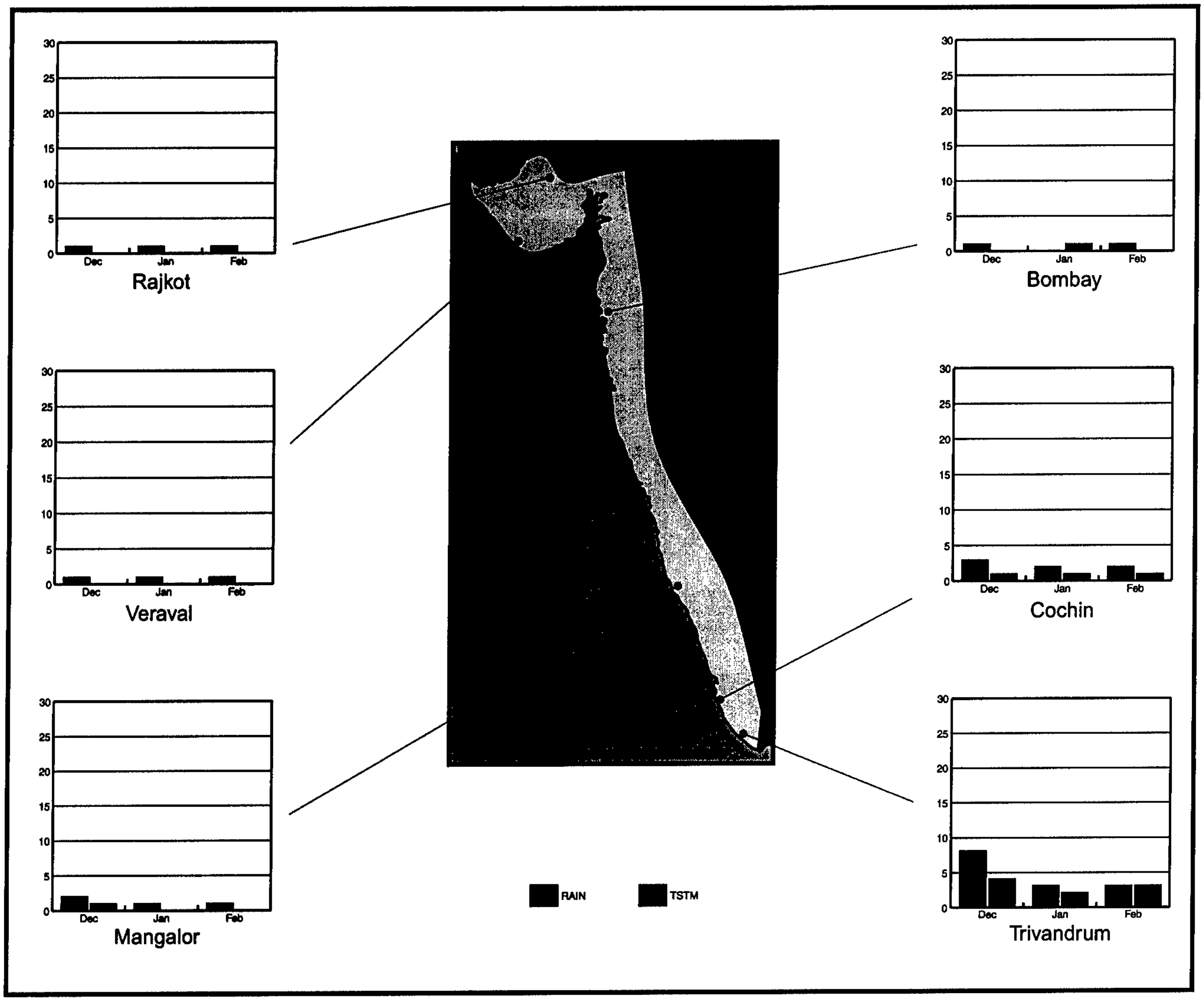


Figure 5-8. Winter Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Mean maximum temperatures are 83° to 87°F (28° to 31°C). Mean minimum temperatures are 58° to 75°F (14° to 24°C). It is somewhat cooler in the far northern part of the area, near Ahmadabad and west to the Gulf of Kutch. This area is away from the coast and the moderating Arabian Sea. The mountains in northwest India and Pakistan are very much lower than the massive Himalayan ranges. During cold outbreaks from the Asiatic high, cooler air flows over these low mountains from the northwest and brings lower temperatures. Although this is the coolest time of the year, extreme maximum temperatures occasionally reach 100°F (38°C) or higher throughout the area. Extreme minimum temperatures generally range from 34° to 64°F (01° to 18°C). Freezing temperatures are very rare. Figures 5-9 and 5-10 show the January mean maximum and minimum temperatures, respectively.

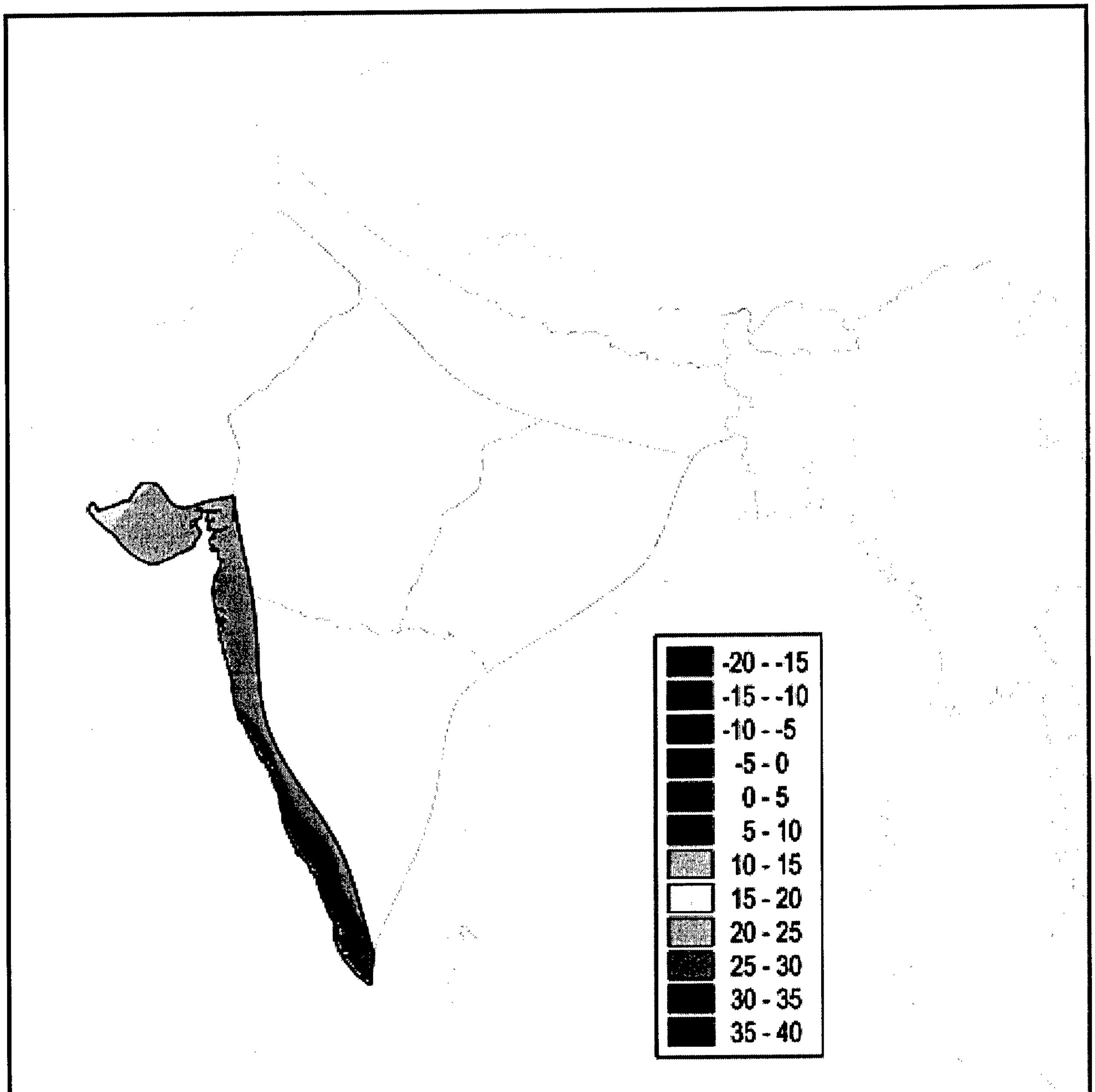


Figure 5-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for the month. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other months may be lower, especially at the beginning and ending of the season.

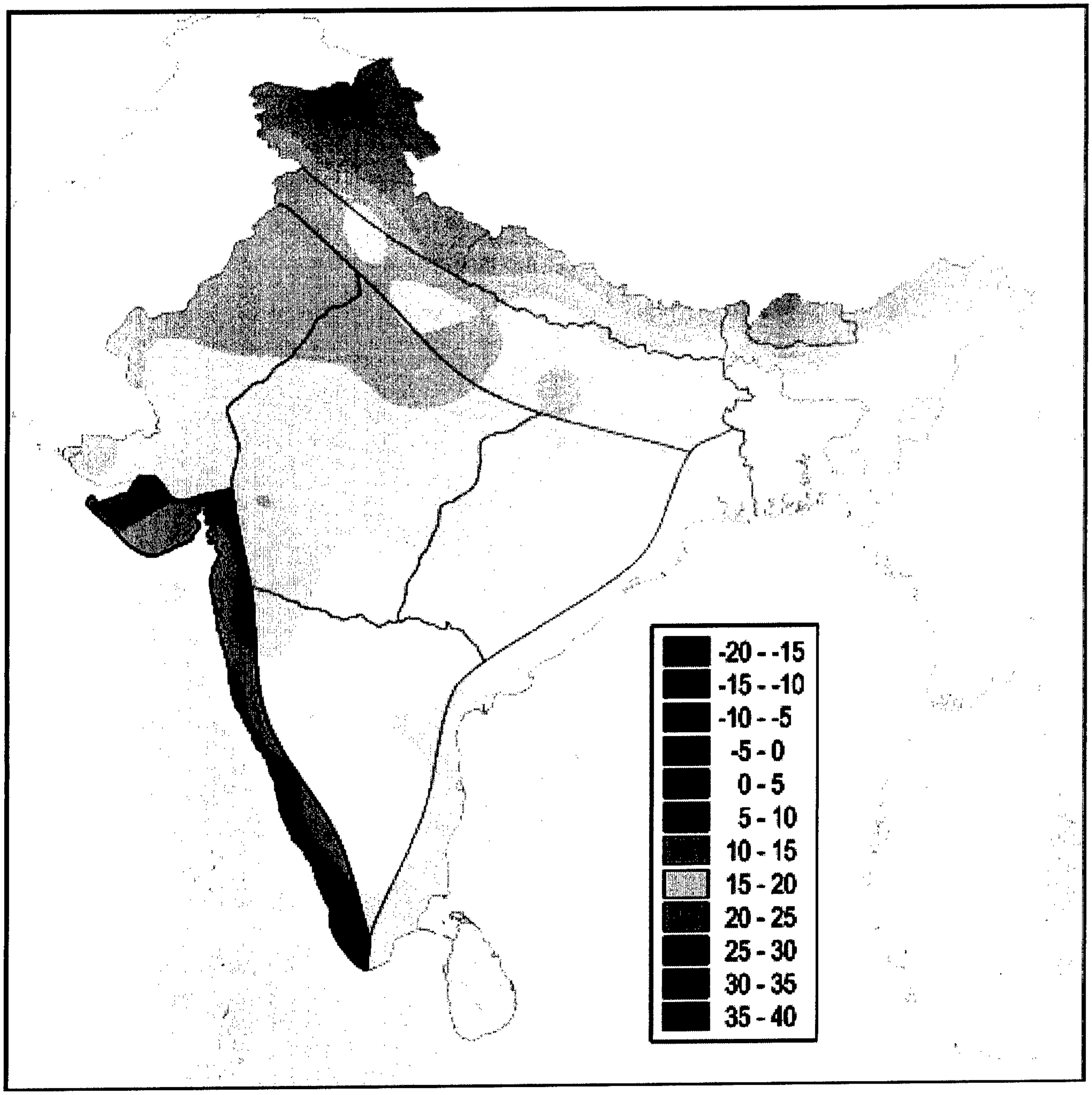


Figure 5-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for the month. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other months may be higher, especially at the beginning and ending of the season.

Hot Season

General Weather. This is the driest and hottest period. The equatorial trough (ET) is far south and the subtropical jet, which helped move systems westward across north India, is over or north of the Himalayas. The sky is often clear. Winds are light and driven by differential heating rather than synoptic features. The transition to the southwest monsoon begins in May. The Asiatic high is significantly weaker and soon disappears. The Southern Hemisphere belt of high pressure builds, and the ET begins to move north. Often by late May, it is over southern India. Strong, often violent, storms begin. This is the "monsoon burst" that announces the arrival of the southwest monsoon. The hot, dry weather is at an end as cloudiness and rains increase rapidly. Typhoons may occur in April and May. Although uncommon, they bring torrential rain, thunderstorms, and destructive winds when they occur. The low coasts may be inundated.

Sky Cover. There is little cloud cover during March and April. The ceiling is below 10,000 feet 10 percent of the time or less at most locations. Cochin and Ratnagiri, in large, swampy areas near the central west coast, experience more cloudiness than most with ceilings below 10,000 feet 40-45 percent of the time. Ceilings below 3,000 feet occur at most locations less than 10 percent of the time. At Cochin and Ratnagiri the ceiling occurs over 20 percent of the time in March and April and up to 39 percent of the time in May. Lower ceilings are rare. Stratus may form during the early morning hours in low, marshy areas and river valleys, but it dissipates with sunrise.

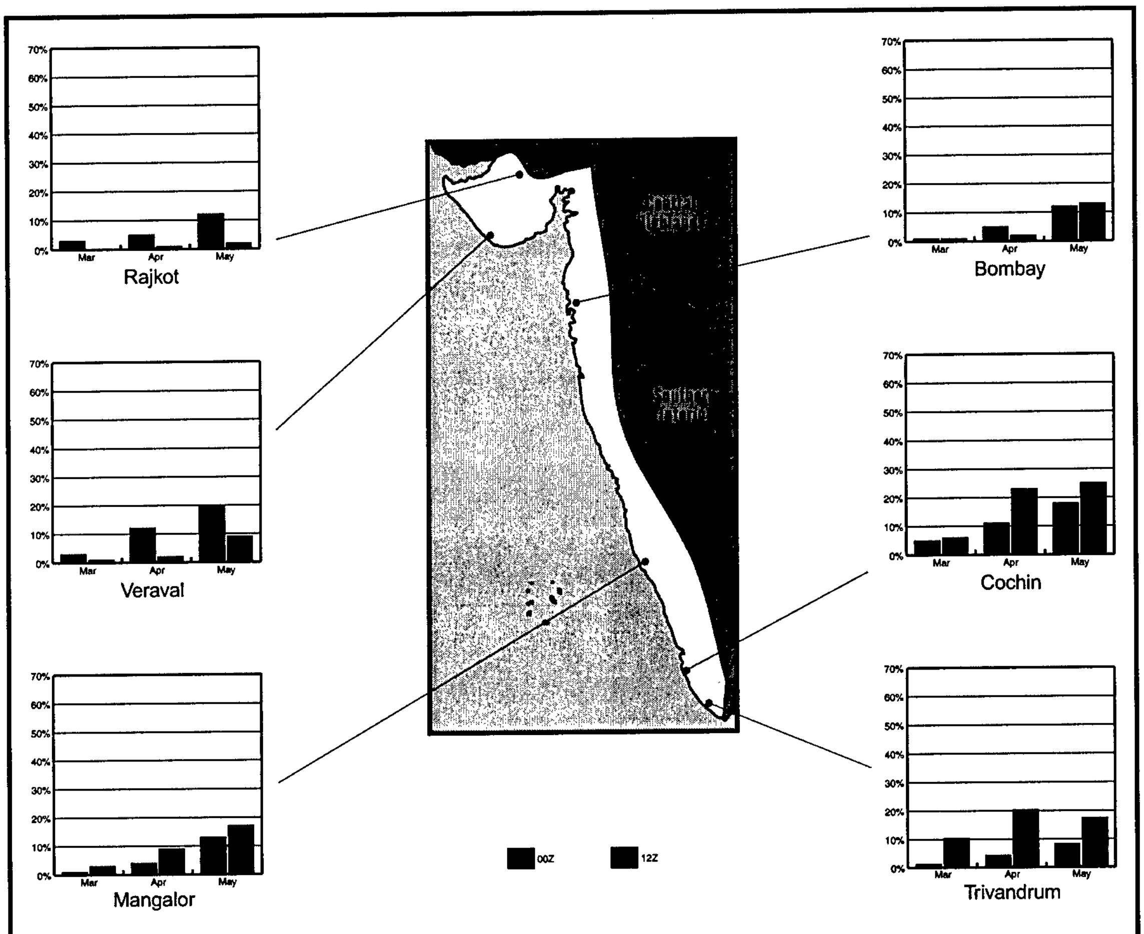


Figure 5-11. Hot Season Percent Frequency of Ceilings below 3,000 Feet. The graphs show a monthly breakdown of the percent frequency of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. Visibility is less than 6 miles (9,000 meters) nearly 100 percent of the time at 2300L in most of the area. By 0800L, it occurs 25-50 percent of the time on the Kathiawar Peninsula and 45-75 percent of the time at Veraval and Bombay. Other stations report it less than 25 percent of the time, except Trivandrum, where it occurs up to 45 percent of the time. During the day, visibility is less than 9,000 meters under 25 percent of the time at most locations. Cochin reports it up to 40 percent of the time.

Except at Cochin, the visibility is less than 2 1/2 miles (4,000 meters) less than 15 percent of the time (see Figure 5-12). Cochin experiences it over 30 percent of the time in March and April and 55 percent of the time in May. Trivandrum has a high incidence of visibility less than 4,000 meters at 2300L, 25-55 percent of the time. Visibility less than 1 1/4 miles (2,000 meters) does not occur at most stations, but Trivandrum gets it 7 percent of the time in May as the ET approaches, and pre-monsoon rains begin on the southern tip of India.

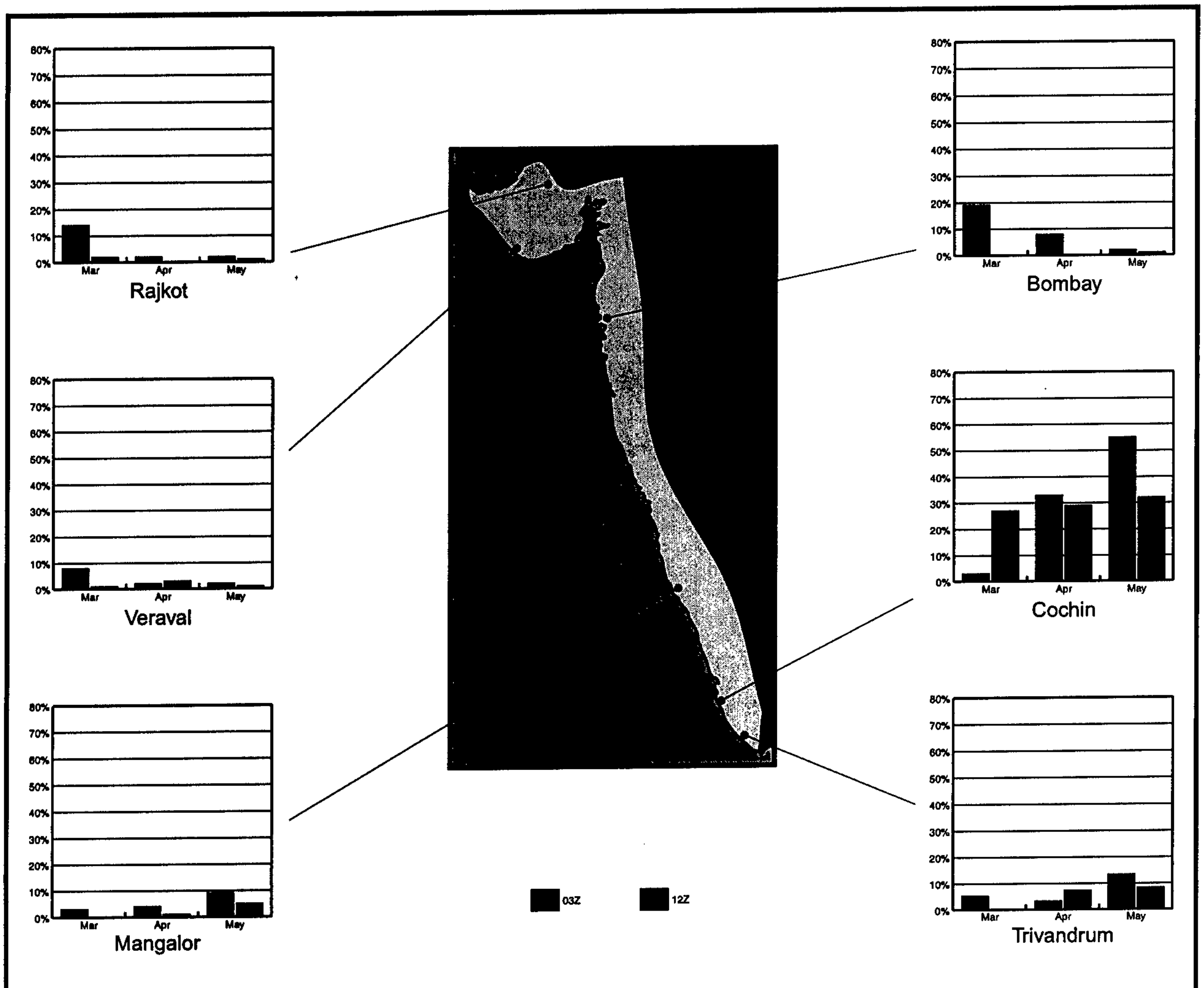


Figure 5-12. Hot Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent frequency of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The winter winds continue during much of the hot season. The large-scale flow is generally under 10 knots from the northwest. The winds on the Kathiawar Peninsula are northwest at 5-10 knots with frequent night calms. Along the coast, a sea breeze at 10-12 knots dominates during the day. A lighter land breeze, usually below 5 knots, takes over at night; night calms are frequent. In mid- to late May, southwest winds start on the tip of the peninsula.

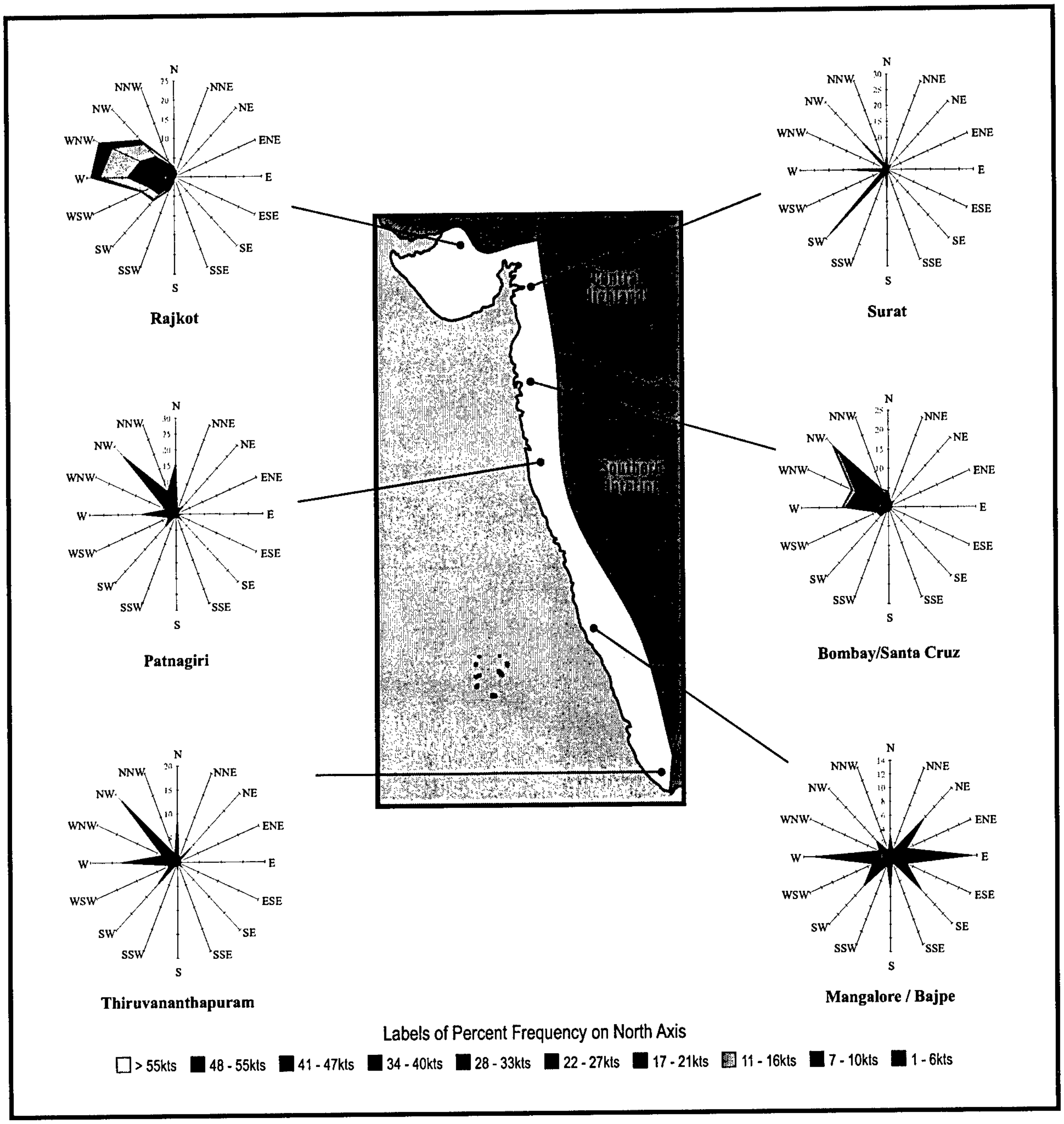


Figure 5-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Two upper-air wind systems are evident during the hot season. In the south, tropical easterlies prevail, and the westerlies are evident over the northern part of the coast. At 500 mb, the winds over all of the west coast are westerly at speeds near 15 knots. Northeast or east winds prevail up to 500 mb in the south and up to 700 mb near the center of the coast. From Bombay north, southwest and west winds exist at 700 mb and higher. Below 700 mb, winds are northwesterly to northerly at 15 knots. The strongest winds are above 300 mb in the far north. The subtropical jet begins to move north near the end of the hot season, but the southern periphery of the jet brings west winds at speeds of up to 100 knots over northern India.

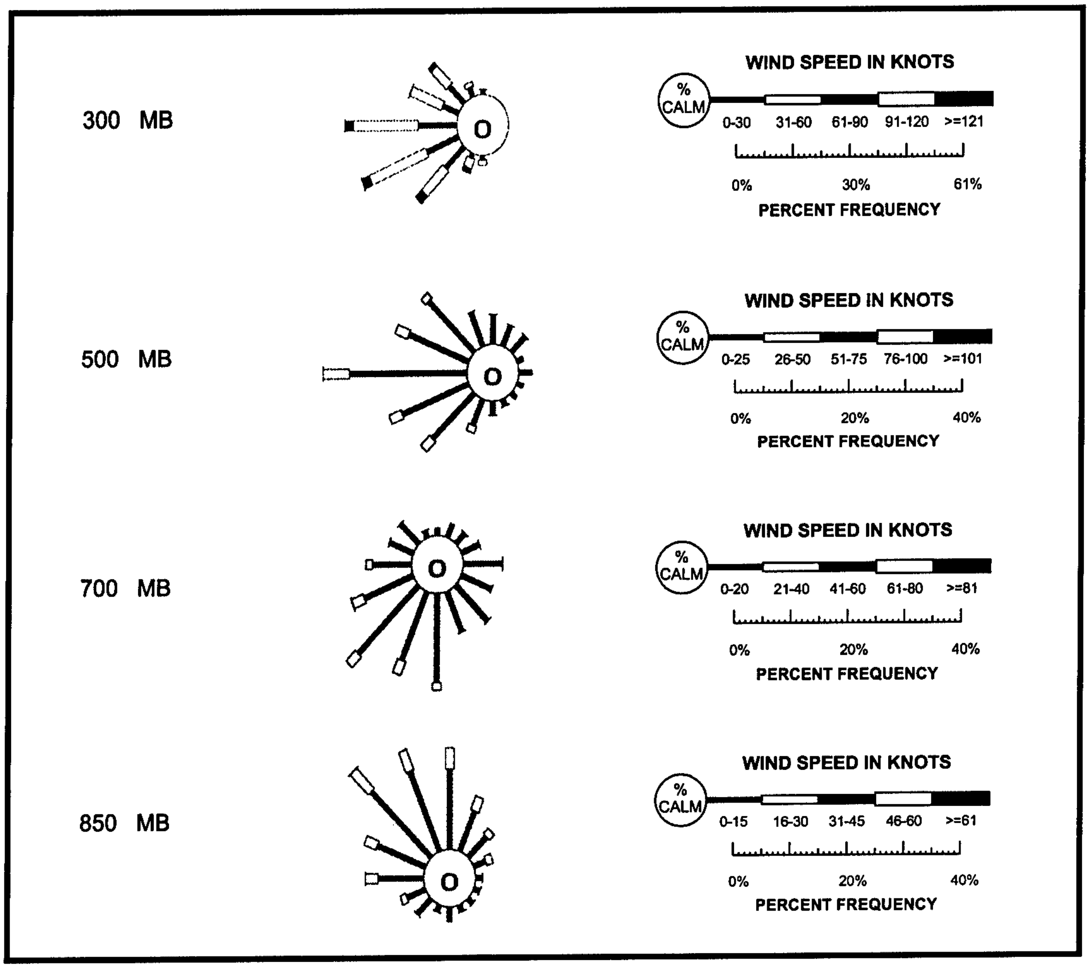


Figure 5-14. April Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Bombay.

Precipitation. Little rain falls on the northern half of the west coast. Rain usually occurs only 1 day per month at many stations, and not at all at other stations. When rain does fall, it is usually less than 0.5 inch (13 mm). Thunderstorms seldom occur. From Panjim to the tip of the peninsula, rain is more frequent. Five inches (128 mm) or more falls in April, and as much as 12.5 inches (318 mm) falls in May. Thunderstorms occur up to half the days of each month. May is a particularly active month on the southwest coast. The ET begins to move north, and as it approaches the tip of the peninsula, strong storms and heavy rains occur fairly frequently. These storms signal the imminent arrival of the southwest monsoon. Figures 5-15 and 5-16 show April mean precipitation amounts and seasonal precipitation and thunderstorm days, respectively.

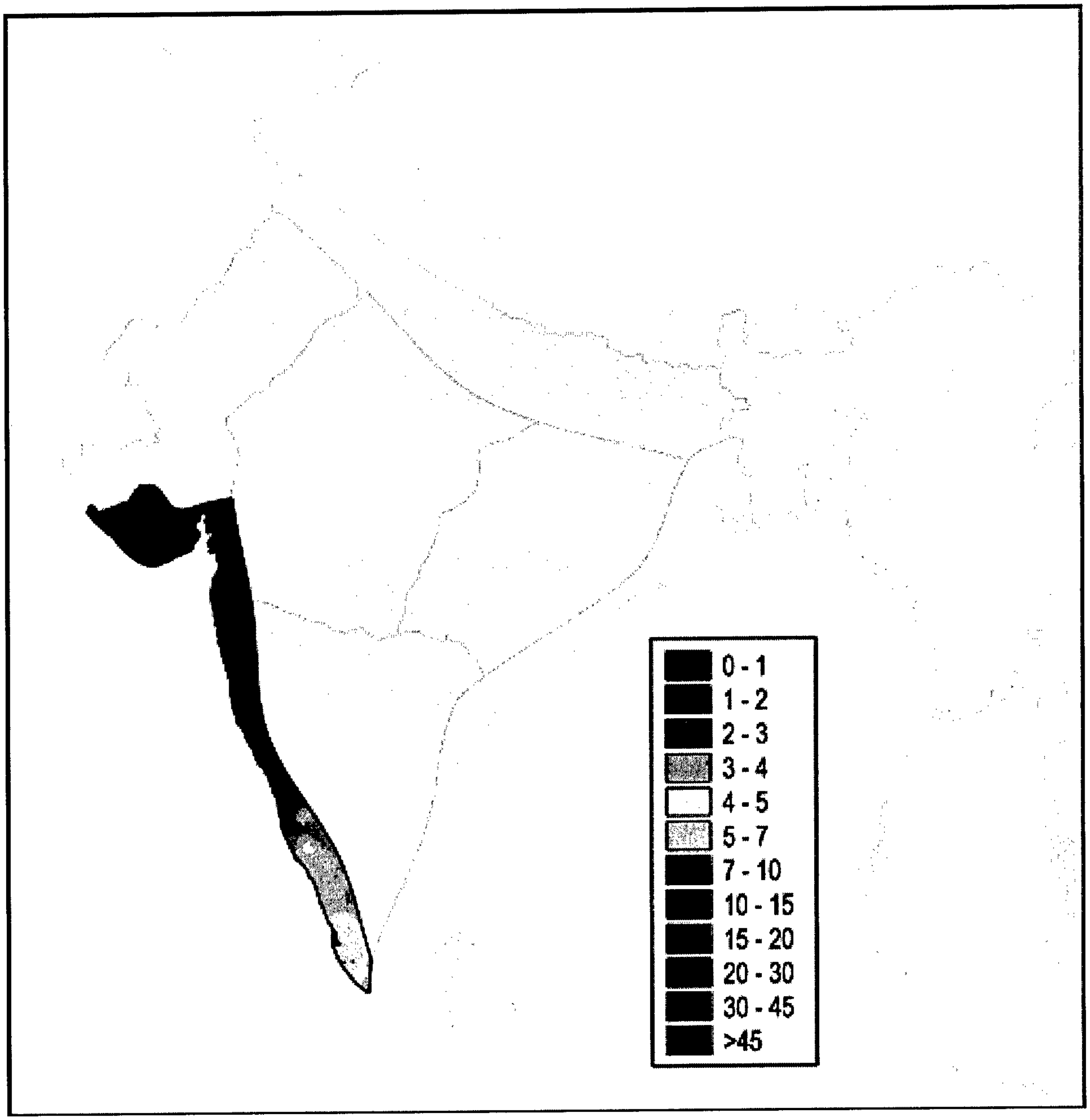


Figure 5-15. April Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

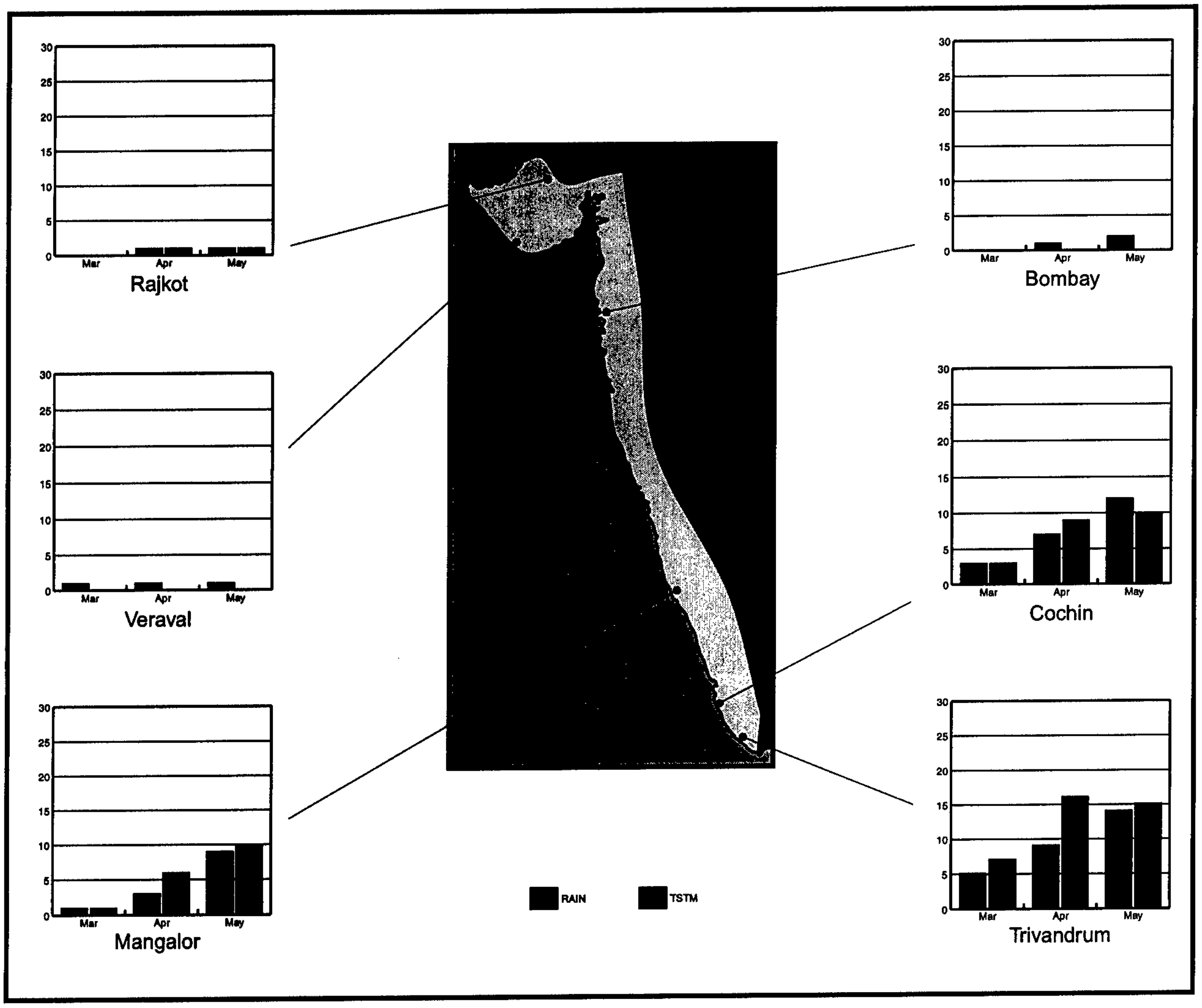


Figure 5-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Mean highs range from 86° to 104°F (30° to 40°C). Mean lows range from 68° to 82°F (20° to 28°C). The northern part of the area is the hottest. Temperatures are often over 100° F (38°C). The mean high near the southern edge of the Thar Desert, is 102°F (39°C) in April, and 104°F (40°C) in May. At Panjim, near the center of the west coast, the mean high is 91°F (33°C) in May. At Trivandrum, near the tip of the peninsula, the mean maximum is 90°F (32°C) in both March and April, and 88°F (31°C) in May. The extreme high reached 117°F (47°C) at Ahmadabad in May. Every station in the area has recorded temperatures over 100°F (38°C) in each month of the hot season. Extreme lows range from 48°F (9°C) in the north to 68°F (20°C) in the south. The April mean maximum and minimum temperatures are seen in Figures 5-17 and 5-18, respectively.

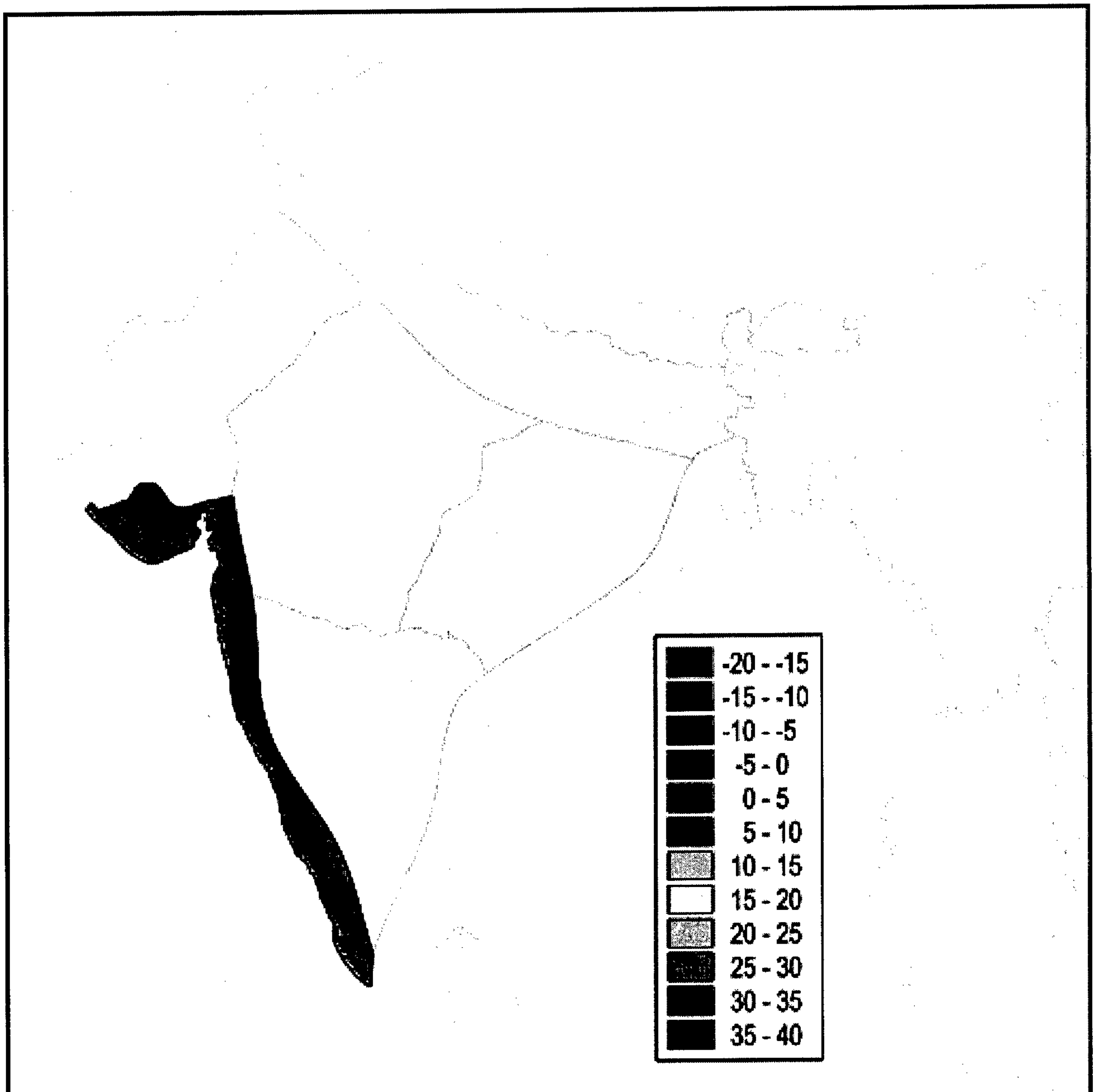


Figure 5-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for the month. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other months may be lower, especially at the beginning and ending of the season.

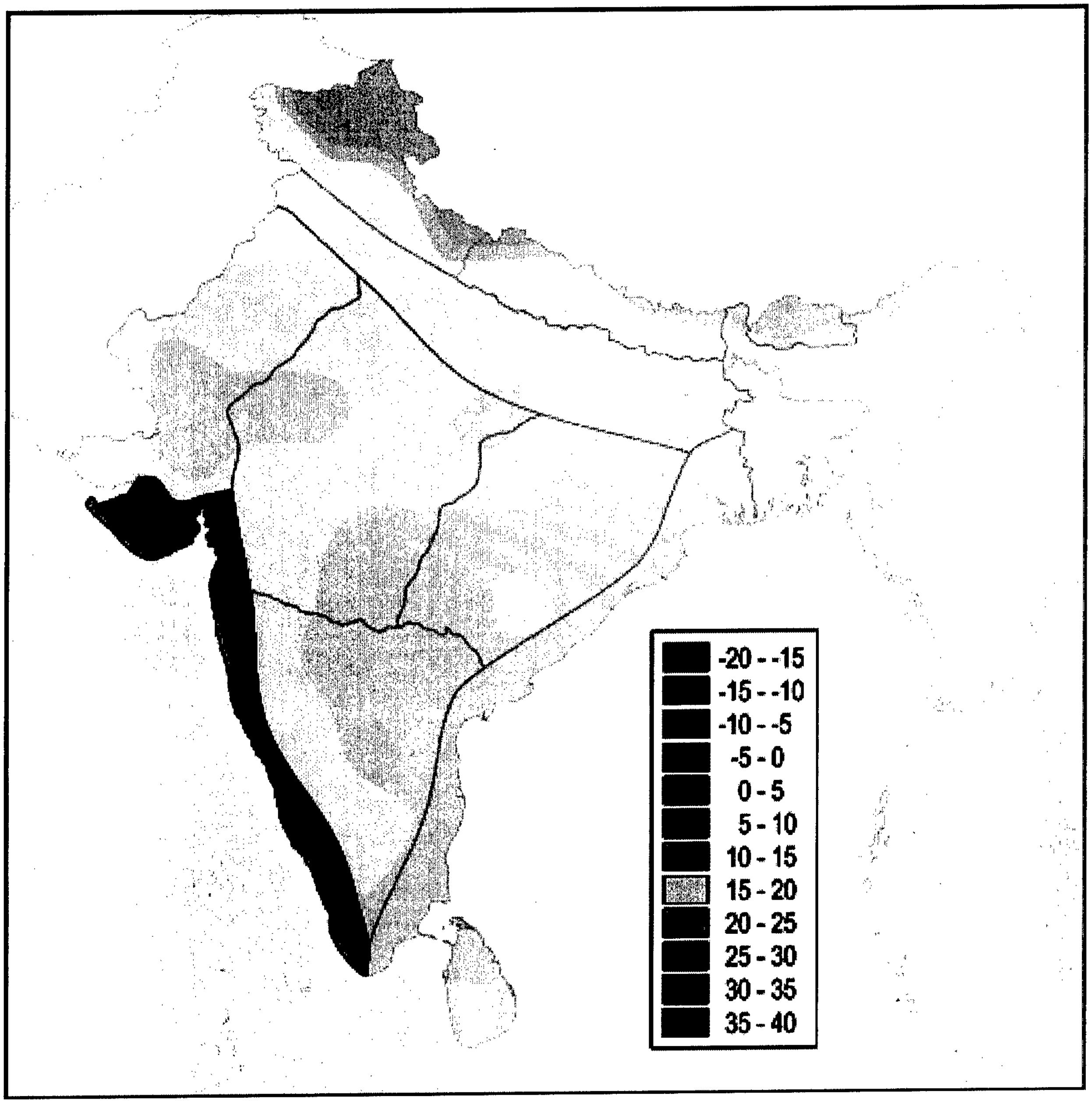


Figure 5-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for the month. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other months may be higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. South Asia's southwest monsoon is a complex interaction among several elements. The equatorial trough (ET) moves north of the Indian subcontinent by the end of June, and the whole area experiences southwest winds. The Somali jet develops and brings a vast flow of warm, moist, unstable air into the northern Indian Ocean. The equatorial westerlies help transport this air over south Asia. Heavy, layered clouds, imbedded thunderstorms, and torrential rains continue throughout the season. The India-Myanmar trough develops over the Bay of Bengal and helps strengthen the tropical easterly jet. The jet provides outflow for convective storms in the bay. Monsoon depressions that develop in the northern Bay of Bengal and track across the peninsula bring more rain to India. The tropical easterlies override the southwest monsoon flow. Easterly waves develop in this strong air current and help monsoon depressions and tropical storms form in the Bay of Bengal. Mid-tropospheric cyclones in the north Arabian Sea bring additional torrential rains to the west coast. A weak ridge forms in the Arabian Sea off the southwest coast. This turns the air stream to the northwest. Precipitation is less along the southwest coast because the winds parallel the coast. In September, the southwest monsoon begins its retreat. The Asiatic low that pulled the ET north vanishes, and the Asiatic high builds. On the way south, the ET usually crosses the northern part of the area in mid to late September. It makes a fairly steady retreat, contrary to its erratic north and south oscillations on its advance north. As the ET passes, heavy rains and thunderstorms accompany it. Behind the ET, the northeast flow reestablishes itself.

This is prime tropical cyclone season. Although most storms develop in the Bay of Bengal, some form in the Arabian Sea as well. It is unusual for Arabian Sea storms to strike the west coast, but it has occurred. Either way, these storms still reach the west coast with high winds and heavy rains. Bay of Bengal storms that reach the west coast are generally those that make first landfall on the southern third of the east coast then cross the peninsula to pound the west coast. This track is most common from June to September.

Sky Cover. Mean cloudiness increases dramatically with the southwest monsoon. Cloudiness averages 70-90 percent coverage in the morning with a small increase in the afternoon. Clouds are mostly low and middle stratiform type. Embedded thunderstorms occur frequently, especially in June when the ET is still on its journey northward. The ceiling is less than 10,000 feet up to 50 percent of the time in the north and as much as 80 percent of the time on parts of the southwest coast. The ceiling is less than 3,000 feet from 30 to nearly 70 percent of the time as seen in Figure 5-19. Ceilings below 1,000 feet occur less than 10 percent of the time. The highest frequency of ceilings at all levels occurs at locations where the Western Ghats are very close to the coast and clouds pile up on the windward slopes. Both Panjim and Kozhikode have lower incidences of ceilings. They are in low, flat plains 50 miles (80 km) or more from the mountains. July and August are the cloudiest months, and September is least cloudy. The southwest monsoon begins its retreat in September so cloudiness decreases rapidly.

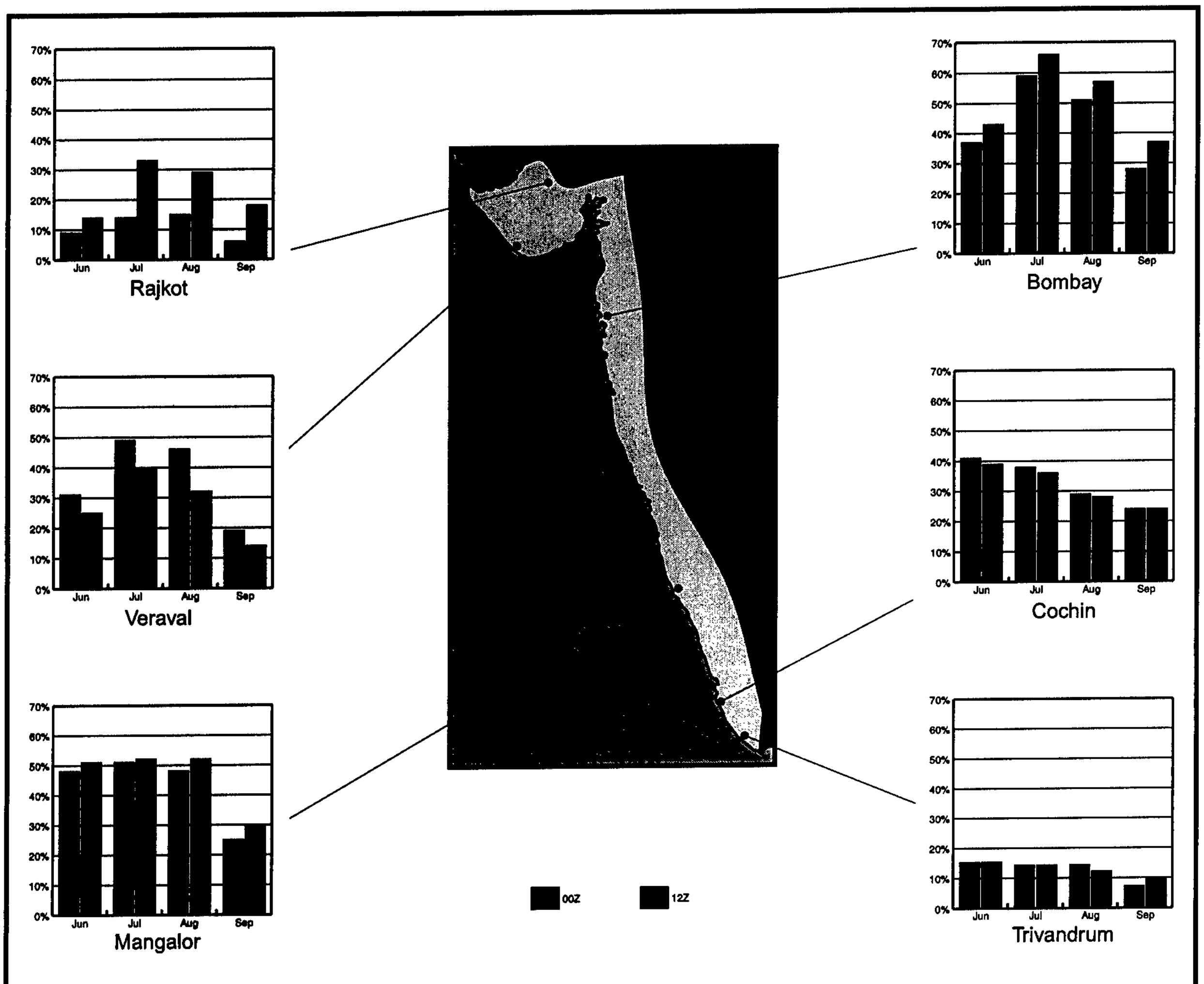


Figure 5-19. Southwest Monsoon Season Percent Frequency of Ceilings below 3,000 Feet. The graphs show a monthly breakdown of the percent frequency of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. As the ET moves north, the southwest monsoon rains drop the visibility to less than 9,000 meters as often as 75 percent of the time at many locations but only 30 percent of the time at other locations. Visibility is most restricted in the morning and least in the afternoons. Even at the height of the monsoon, visibility is mainly better than 2 1/2 miles (4,000 meters). Cochin gets visibility below 4,000 meters 75 percent of the time in June and 47 percent of the time in September. Other coastal stations have below 4,000 meters conditions up to 50 percent of the time. On the Kathiawar Peninsula, visibility is less than 4,000 meters 10 percent of the time or less. Figure 5-20 shows the percent frequency of visibility below 4000 meters at selected locations in this region. Visibility less than 1 1/4 miles (2,000 meters) is rare. It occurs 15 percent of the time or less at southern stations and under 10 percent of the time farther north. Figure 5-20 illustrates the percent frequency of visibility below 4,000 meters at selected Western Coastal Plain locations.

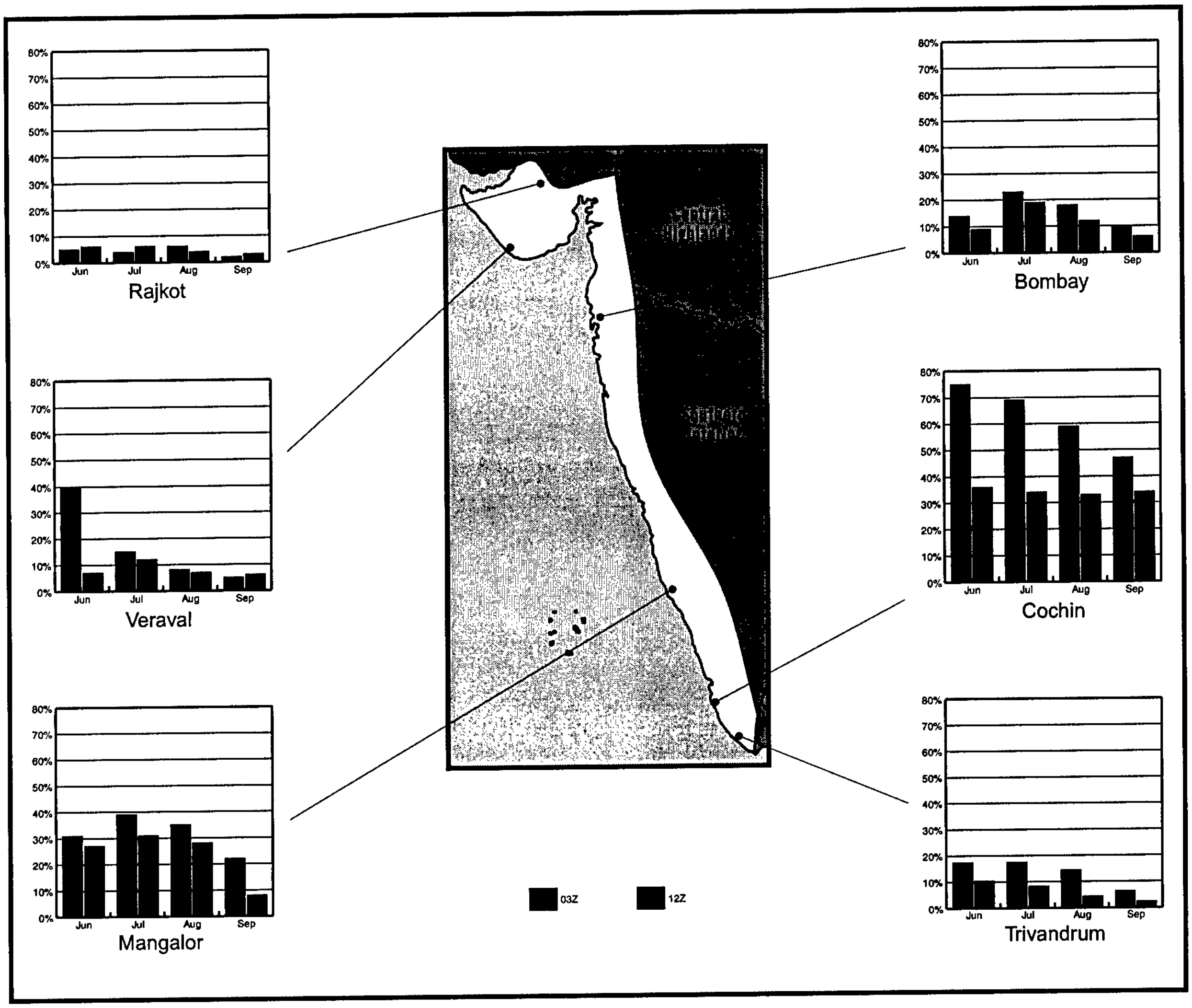


Figure 5-20. Southwest Monsoon Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent frequency of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Winds are generally from the west along the coast at 8-12 knots during the day and slightly less at night. Along most of the coast, the wind is from the southwest. Farther south, at Kozhikodi and Cochin, the wind is from the northwest. This is due to a weak surface ridge in the eastern Arabian Sea. The India-Myanmar trough in the Bay of Bengal draws in westerly flow from the Indian Ocean and turns it toward the southeast as it nears the trough in the southern part of the bay. Figure 5-21 shows wind roses for representative stations in the Western Coastal Plain.

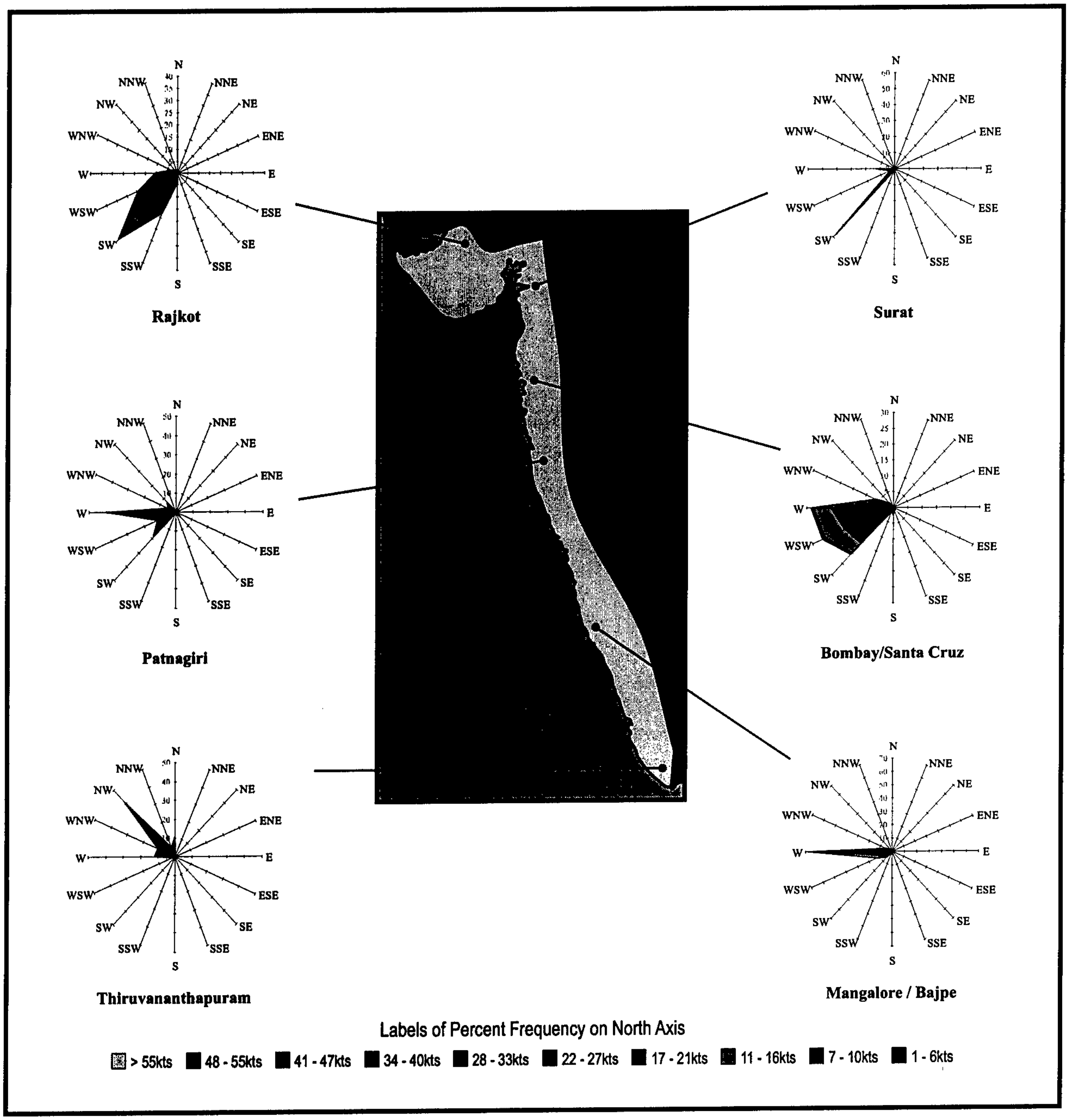


Figure 5-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Only the monsoon westerlies and the tropical easterlies are over the western coastal plains. The equatorial westerlies are over the extreme north. The monsoonal westerlies reach the 400 mb level in the south and the 700 mb level in the north (Kathiawar Peninsula). At 300 mb, the tropical easterlies prevail over the entire area. Winds in the monsoon westerlies are generally 25-50 knots. The strongest winds are near the 700 mb level from Bombay south, up to 60 knots. In the tropical easterlies, wind speeds are generally near 30 knots, but reach 60 knots at higher levels. The strongest winds are at and above 300 mb. Figure 5-22 shows the upper-level winds over Bombay.

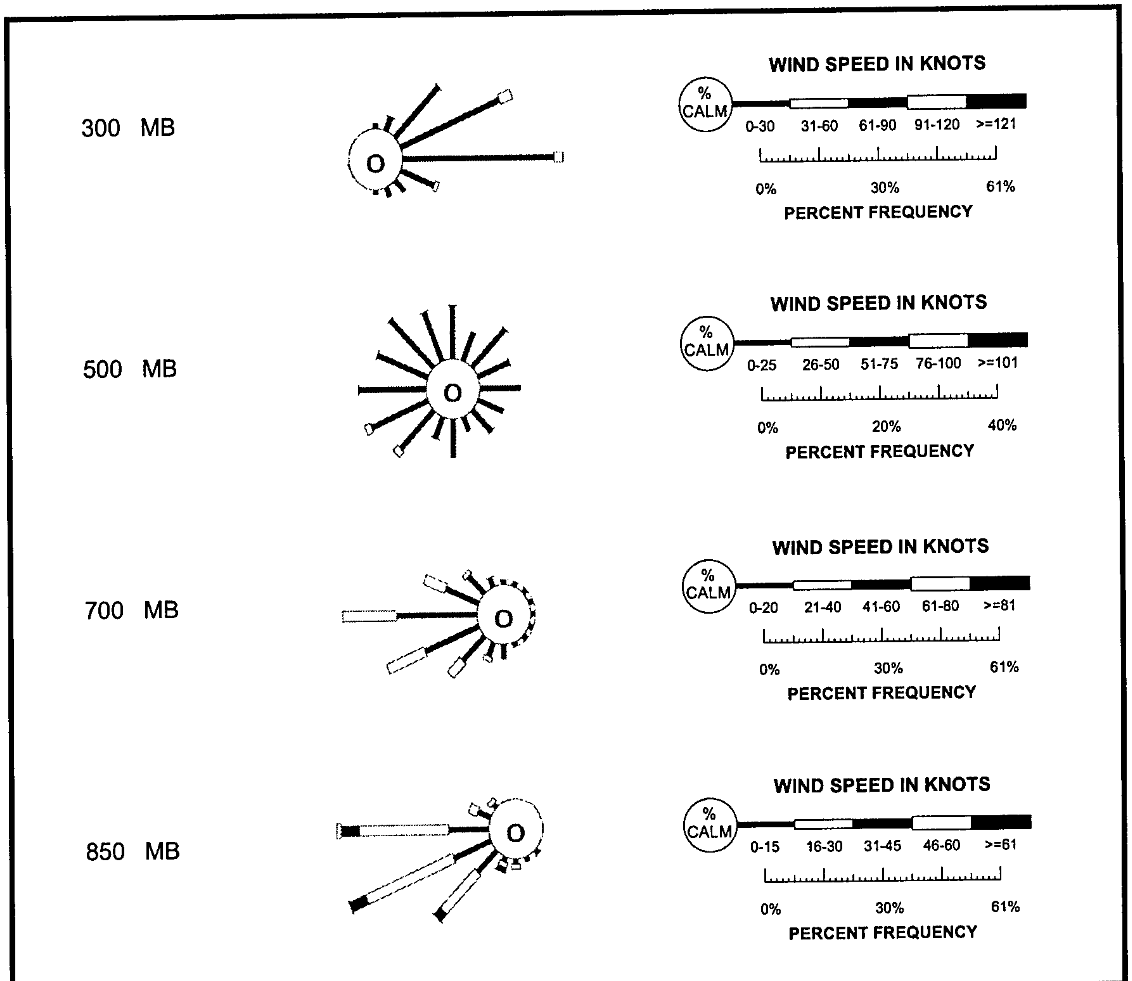


Figure 5-22. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Bombay.

Precipitation. Rainfall increases dramatically in June. Ahmadabad gets 3.6 inches (91 mm) of rain in June and 11.8 inches (300 mm) in July. Other northern stations experience similar amounts. Precipitation decreases in August and September; mean amounts range from 1.5 to 6 inches (38 to 152 mm) in September in the north. From Bombay south, rainfall is much heavier. Up to 26 inches (660 mm) falls at Bombay in July. Mangalore usually gets 39 inches (991 mm) of rain in July. The southern-most stations receive their maximum rainfall in June when Cochin gets 22 inches (559 mm) and Trivandrum gets 13 inches (330 mm). The weak ridge in the Arabian Sea, and the northwest wind flow, nearly parallel to the coast, suppresses rainfall at the southernmost stations.

Rain falls 19 days in July and August in the far north and almost every day in July and August as far south as Mangalore. The southernmost stations get rain up to 25 days per month all season. Thunderstorms occur 10 days in June and 7 days in July at Mangalore. The Kathiawar Peninsula gets them up to 6 days in July at Ahmadabad, but only 1 or 2 days at other sites. The coast has thunderstorms 3-7 days per month. Convective activity increases in September as the ET moves south. Figures 5-23 and 5-24 show the precipitation amounts in July and the seasonal rain and thunderstorm days at selected Western Coastal Plain locations, respectively.

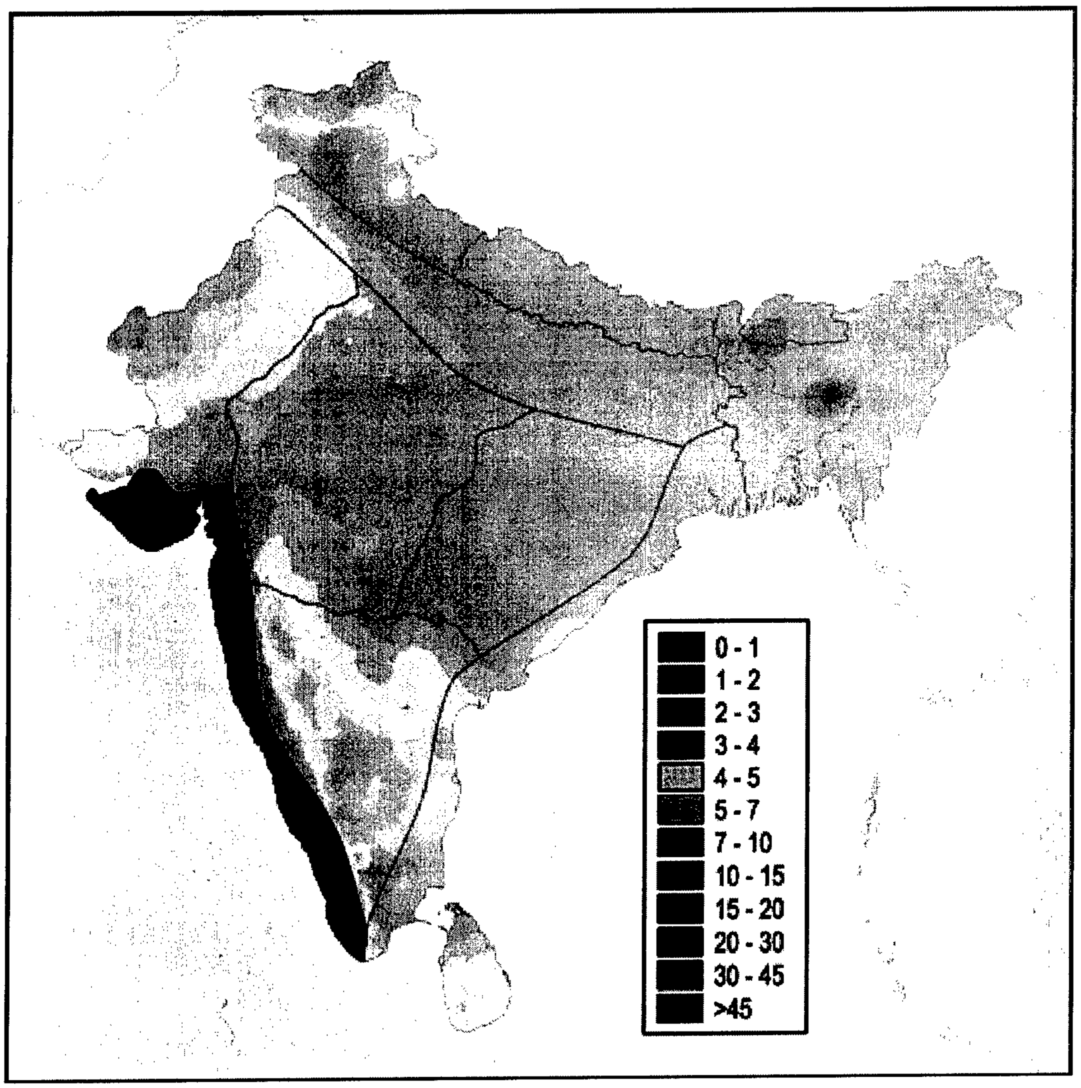


Figure 5-23. July Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

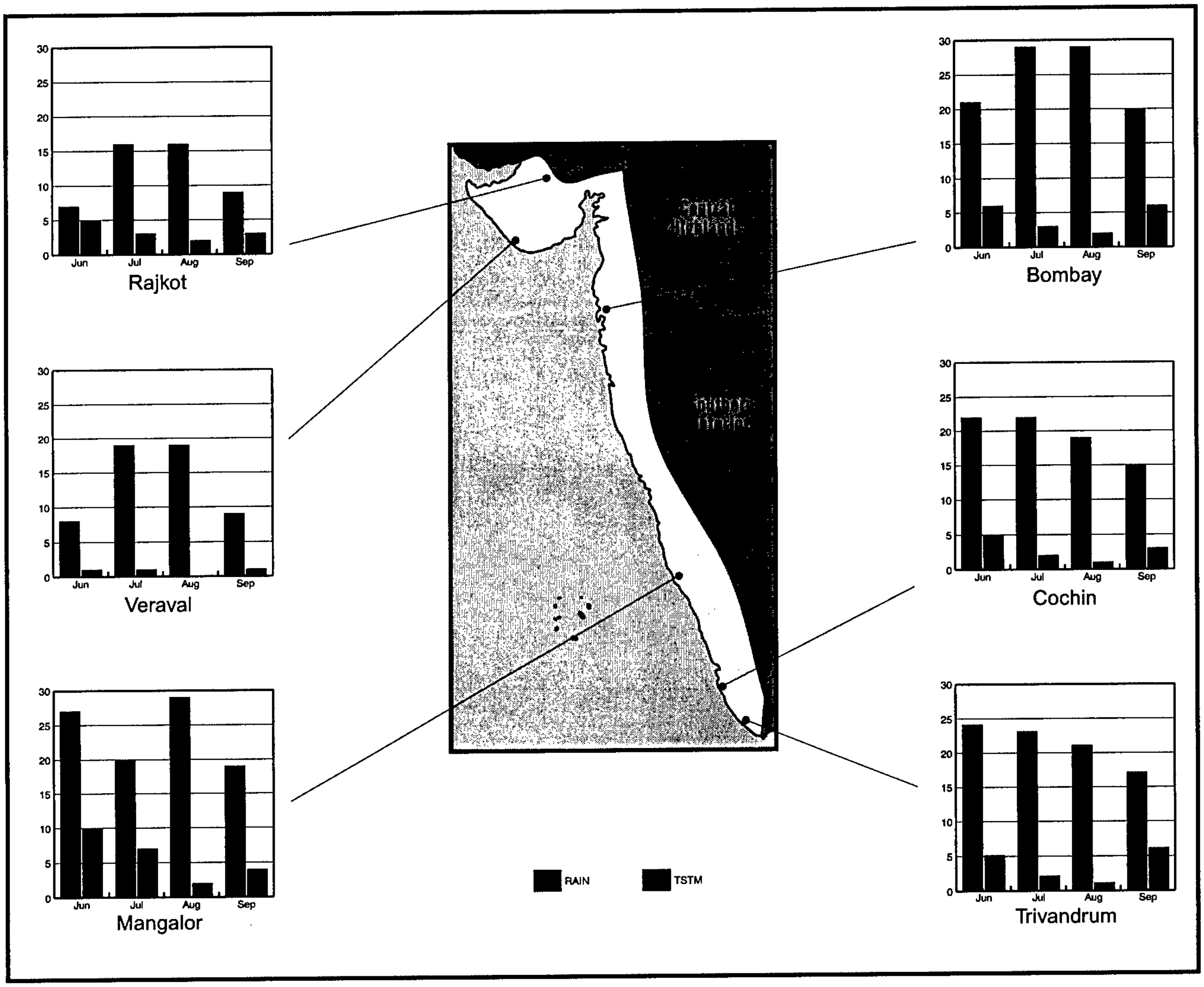


Figure 5-24. Southwest Monsoon Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Temperatures are hot during the season, but are moderated by the clouds and rainfall that increase so rapidly with the onset of the southwest monsoon. At stations on the Kathiawar Peninsula, the mean highs are 88° to 100°F (31° to 38°C). On the coastal plains, the mean highs are 81° to 88°F (27° to 31° C). Mean minimums are 75° to 82°F (24° to 28°C). Monthly variations of mean highs and lows are small during the season, generally 5 Fahrenheit (3 Celsius) degrees or less. In the far north, just south of the Thar Desert, the monthly variation is 10 Fahrenheit (6 Celsius) degrees. Very high temperatures may occur during the season. All stations have experienced extreme highs over 100°F (38°C). Ahmadabad's extreme high in June is 118°F (48°C). Extreme lows range from 57° to 72°F (14° to 22°C). Figures 5-25 and 5-26 show the July mean high and low temperatures at selected Western Coastal Plain stations, respectively.

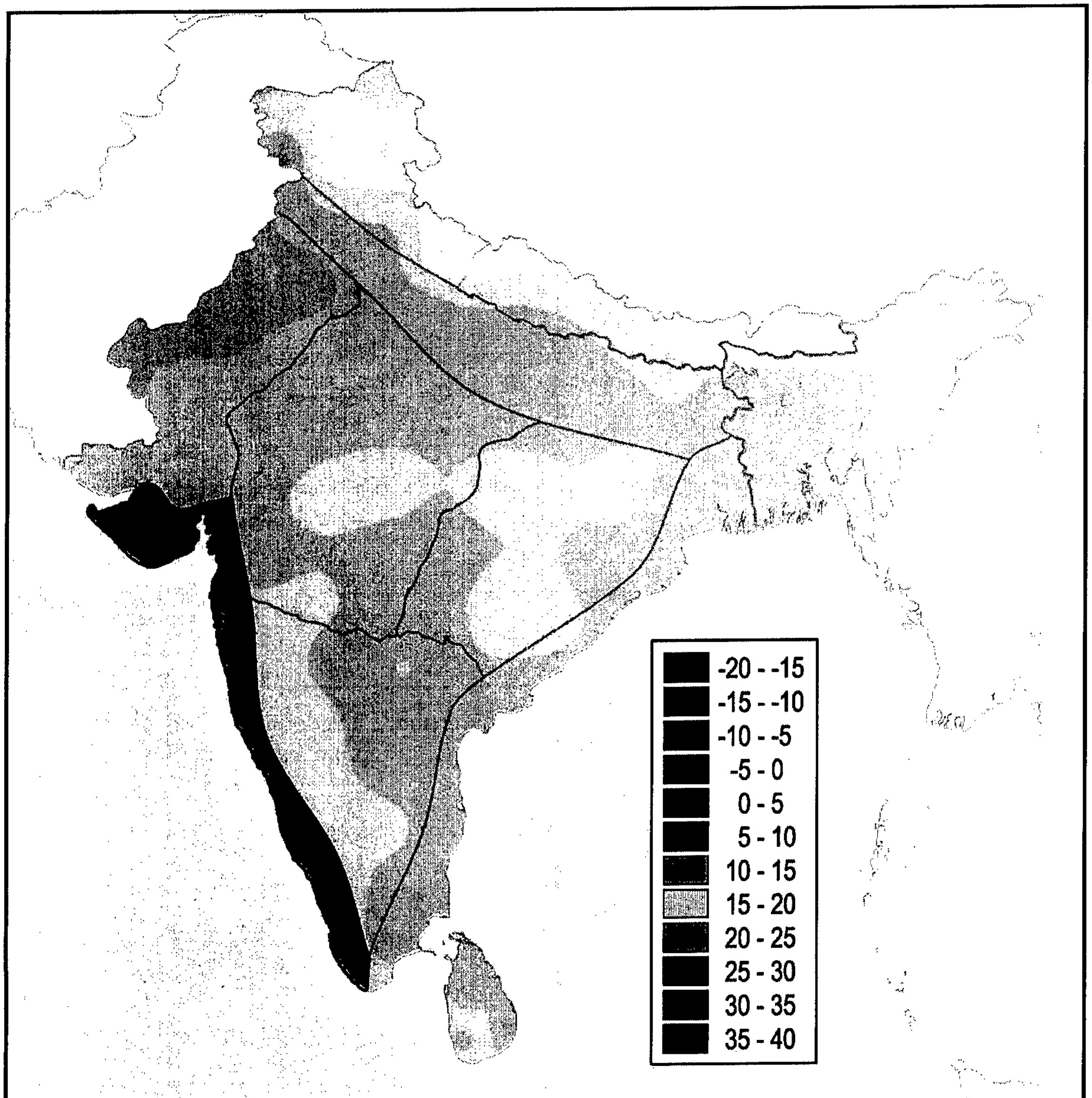


Figure 5-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for the month. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other months may be lower, especially at the beginning and ending of the season.

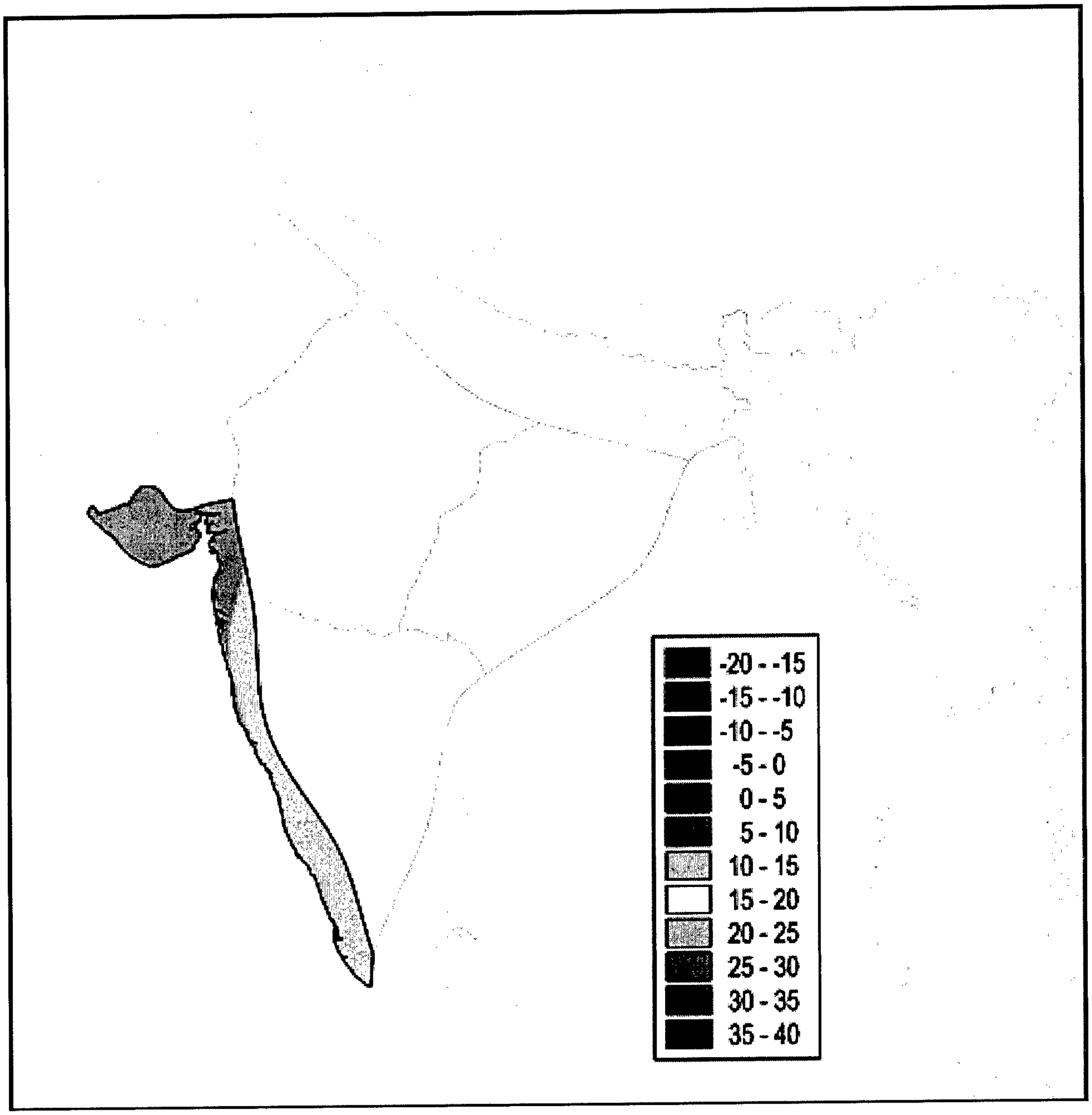


Figure 5-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for the month. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other months may be higher, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. By October, the Asiatic high is stronger, and the North Pacific high begins to move south. In response, the equatorial trough (ET) moves south. It usually clears the southern tip of India in late November or early December. As it passes, heavy rain and thunderstorms occur. The elements that drive the southwest monsoon disappear. The upper-level easterlies move well south, and the subtropical jet moves south of the Himalayas. This opens the path for early season westerly disturbances to ride the jet across northern India. October and November are the most active period for tropical storm development, especially in the Bay of Bengal. These storms can become very violent and bring torrential rains and strong winds to the peninsula as they track from the Bay of Bengal across the southern third of the peninsula to reach the west coast. By the end of November, northeast flow is established..

Sky Cover. Cloud cover decreases rapidly in October and November, but the ET usually keeps the southernmost areas cloudy until the end of November. The ceiling is below 10,000 feet at Cochin 45-60 percent of the time in October and 30-50 percent of the time in November. North of Bombay, the ceiling is less than 10,000 feet up to 10 percent of the time in October and 3-7 percent of the time in November. Stations south of Bombay generally have this ceiling 10-25 percent of the time. Mangalore, in the middle of a large, swampy drainage plain, reports the ceiling less than 10,000 feet 45 percent of the time in October and 24 percent of the time in November.

Ceilings below 3,000 feet (see Figure 5-27) reflect the pattern for higher ceilings. Stations from Bombay north report the ceiling below 3,000 feet less than 10 percent of the time. Farther south, it occurs up to 25 percent of the time. Cochin is more cloudy; here the ceiling occurs nearly 30 percent of the time in October and over 20 percent of the time in November. Ceilings below 1,000 feet are rare. Low stratus ceilings will form over swampy areas and in river valleys during early morning hours. The ceilings dissipate with sunrise.

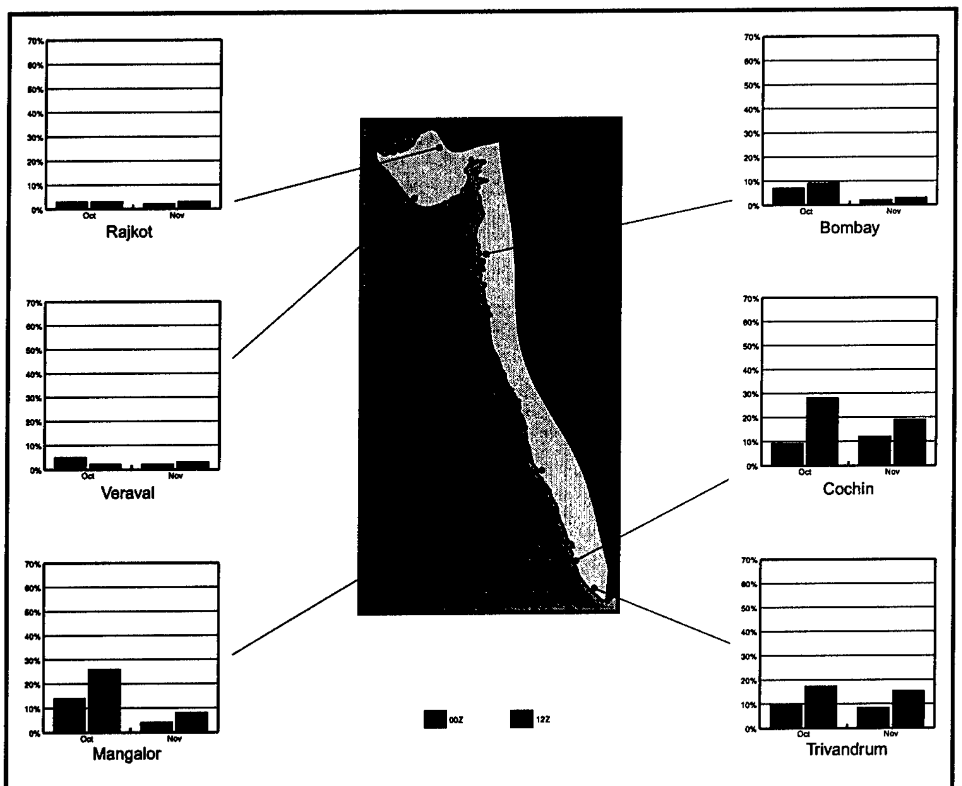


Figure 5-27. Post-Monsoon Season Percent Frequency of Ceilings below 3,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. During the day, visibility is less than 6 miles (9,000 meters) less than 35 percent of the time at most locations, and in the far north, it occurs less than 10 percent of the time. A drop in visibility to•is below 6 miles (9,000 meters) occurs 90-100 percent of the time at 2300L. At 0800L, it occurs less than 50 percent of the time at most locations, but as seldom as 15-20 percent of the time at a few.

Only Cochin reports a significant occurrence of visibility less than 2 1/2 miles (4,000 meters). Here it occurs over 45 percent of the time at 0800L and 35 percent of the time during the day. At other stations, the frequency is usually less than 20 percent of the time as seen in Figure 5-28. Visibility below 1 1/4 miles (2,000 meters) occurs less than 6 percent of the time at all locations.

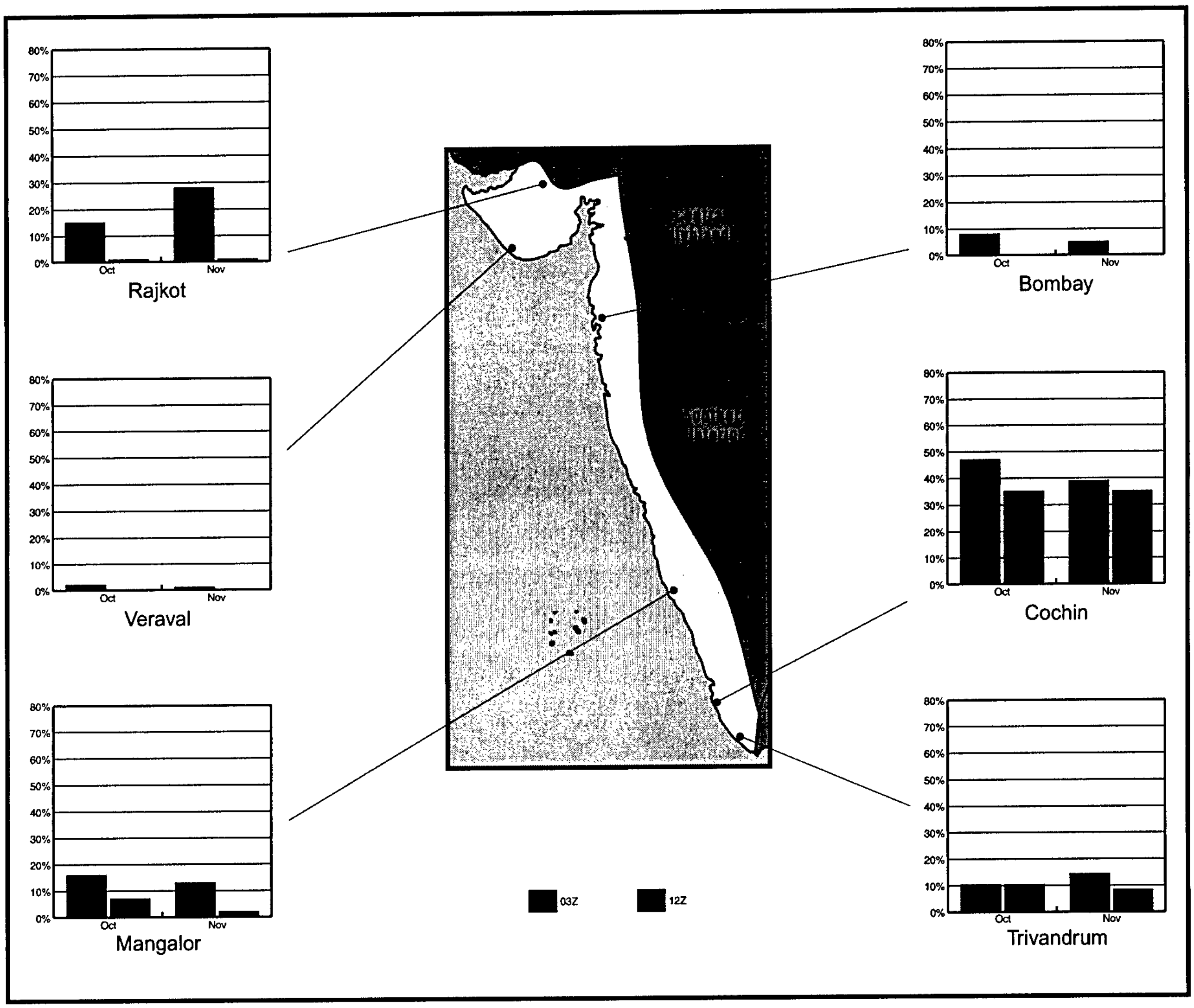


Figure 5-28. Post-Monsoon Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent frequency of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The ET and southwest monsoon retreat southward during this season. Light northerly winds prevail over most of the coastal plains at speeds of 10 knots or less. Since the ET frequently does not clear the southern tip of India until late November or early December, the southern stations are still in the southwest monsoon flow. Winds at both Cochin and Trivandrum frequently are from the northwest until the beginning of the winter season in December. With the retreat of the monsoon, a sea and land breeze pattern is established. At Panjim, the winds are from the west during the day 30 knots, with a maximum speed of 60 knots. This jet is evident over Trivandrum as late as November. Wind roses for representative stations in October are shown in Figure 5-29.

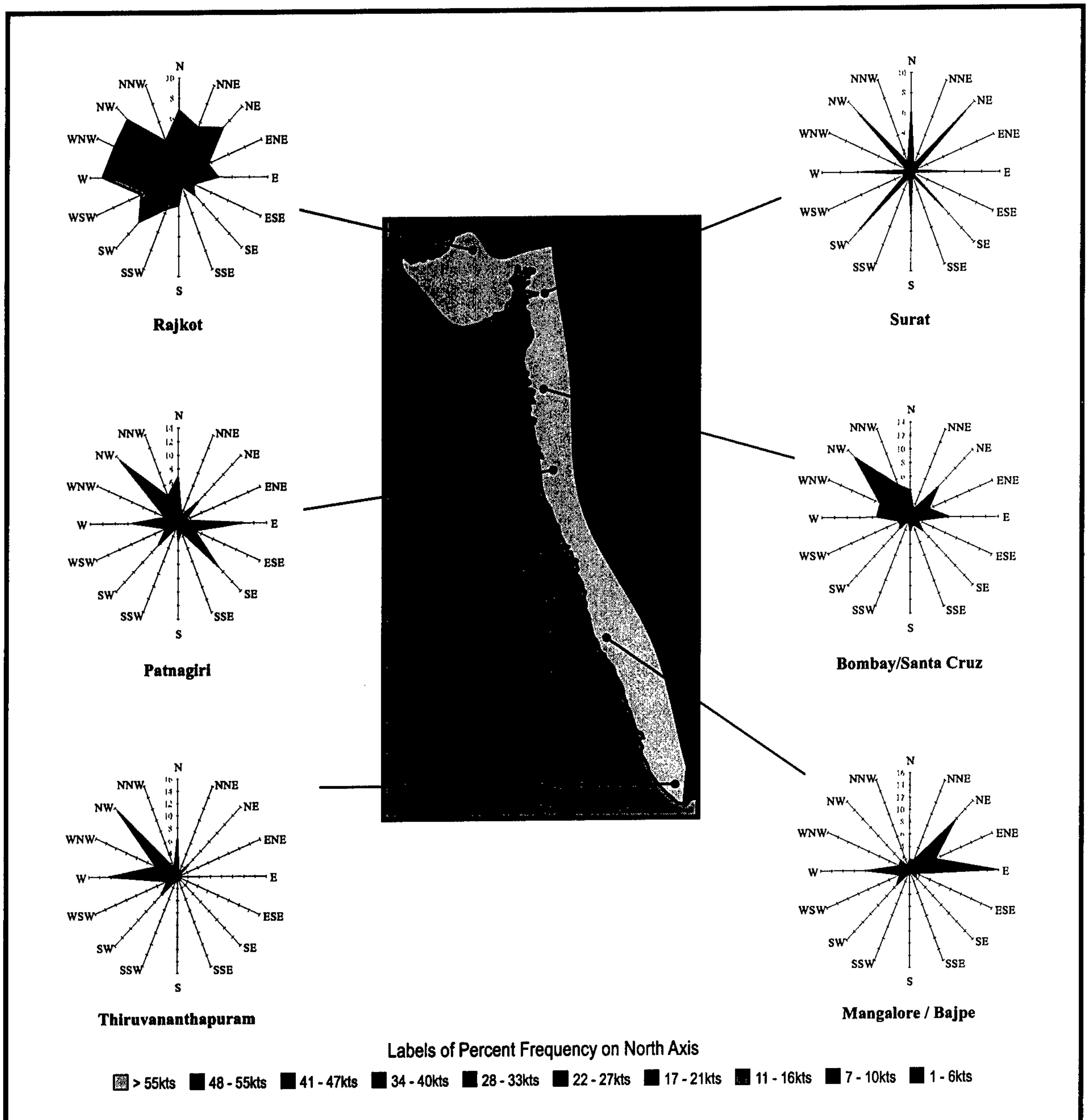


Figure 5-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. From Panumbar north, the upper-air winds are from the northeast and east to 700 mb. Mean speeds are 15-25 knots, with a maximum of 40 knots. Winds at 500 mb are variable in direction at speeds near 25 knots; the maximum speed is 50 knots. At Bombay, 300 mb winds reflect the southward movement of the tropical westerlies. Winds are from the west at 30 knots, with maximum winds up to 60 knots. In the south, still under southwest monsoonal flow, the winds are from the west or northwest to 700 mb. Speeds are 15-30 knots, occasionally 40 knots. Winds at 500 mb are variable at speeds near 25 knots. The tropical easterly jet still exists over the southern part of the area. At 300 mb, the wind is from the east at 30 knots, with a maximum speed of 60 knots. This jet is evident over Trivandrum as late as November. Figure 5-30 shows October upper-level winds for Bombay.

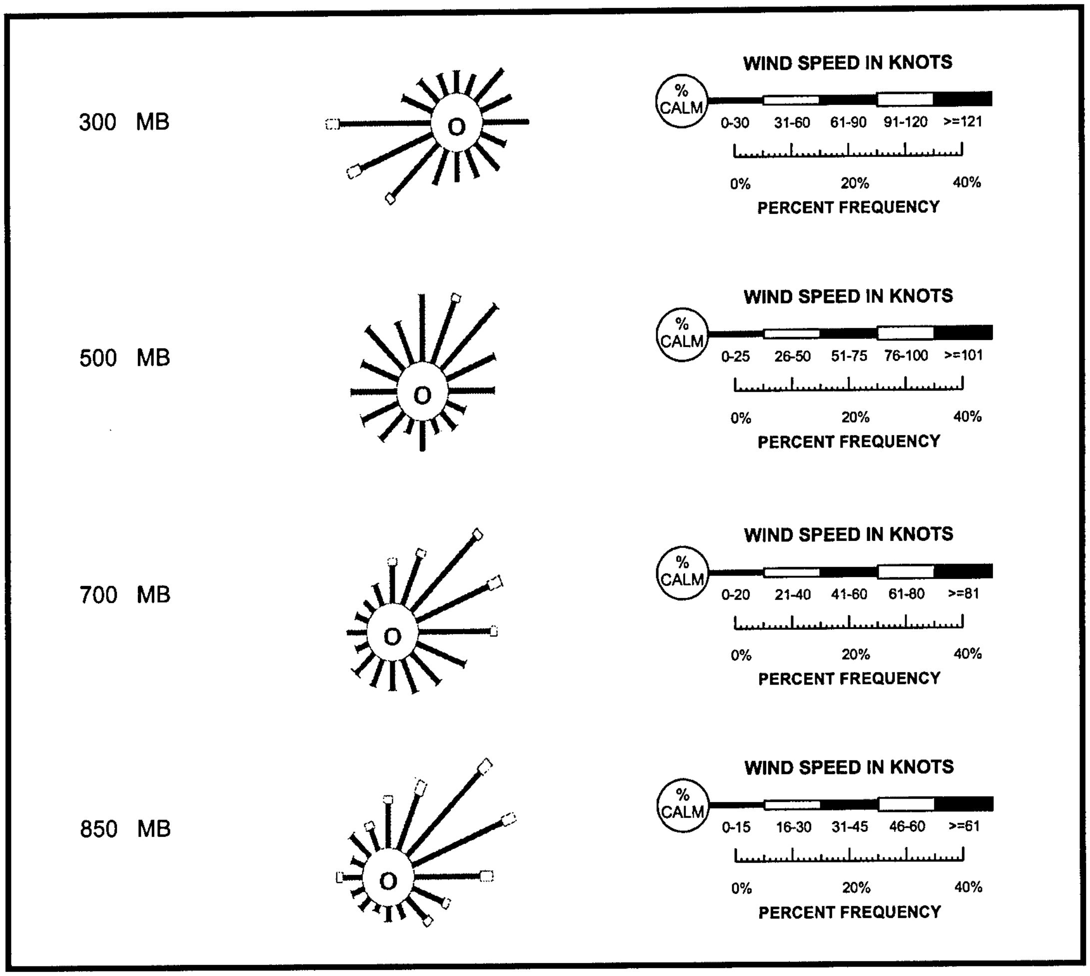


Figure 5-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Bombay.

Precipitation. Rainfall decreases significantly in October except at the southern-most stations, where the ET causes increased rainfall. November brings a further decrease in rainfall, although the southern stations are still very wet. Rain falls only 1-2 days each month in the far north, 2-6 days on the central coast, and as often as 13 days per month at the southern stations. Thunderstorms occur only 1-2 days per month in the north and 2-6 per month along the central coast. They are more frequent in the south. At Trivandrum, thunderstorms occur 13 days in October and 12 days in November. In December, the first month of the winter season, the ET clears the tip of the peninsula, and the southern stations show a sharp decrease in rainfall and thunderstorm frequency. Rainfall amounts range from 0.5 inch (13 mm) at Ahmadabad to 3.8 inches (97 mm) at Panjim in October. In November, the range is 0.2-1.3 inches (5 mm-33 mm) in the same area. October amounts in the southern part of the area are 8.2 to 12.5 inches (208-318 mm). In November, the range is 2.9-7 inches (74-178 mm). Figure 5-31 shows the mean precipitation amounts for October, and Figure 5-32 shows the seasonal precipitation and thunderstorm days for the region.

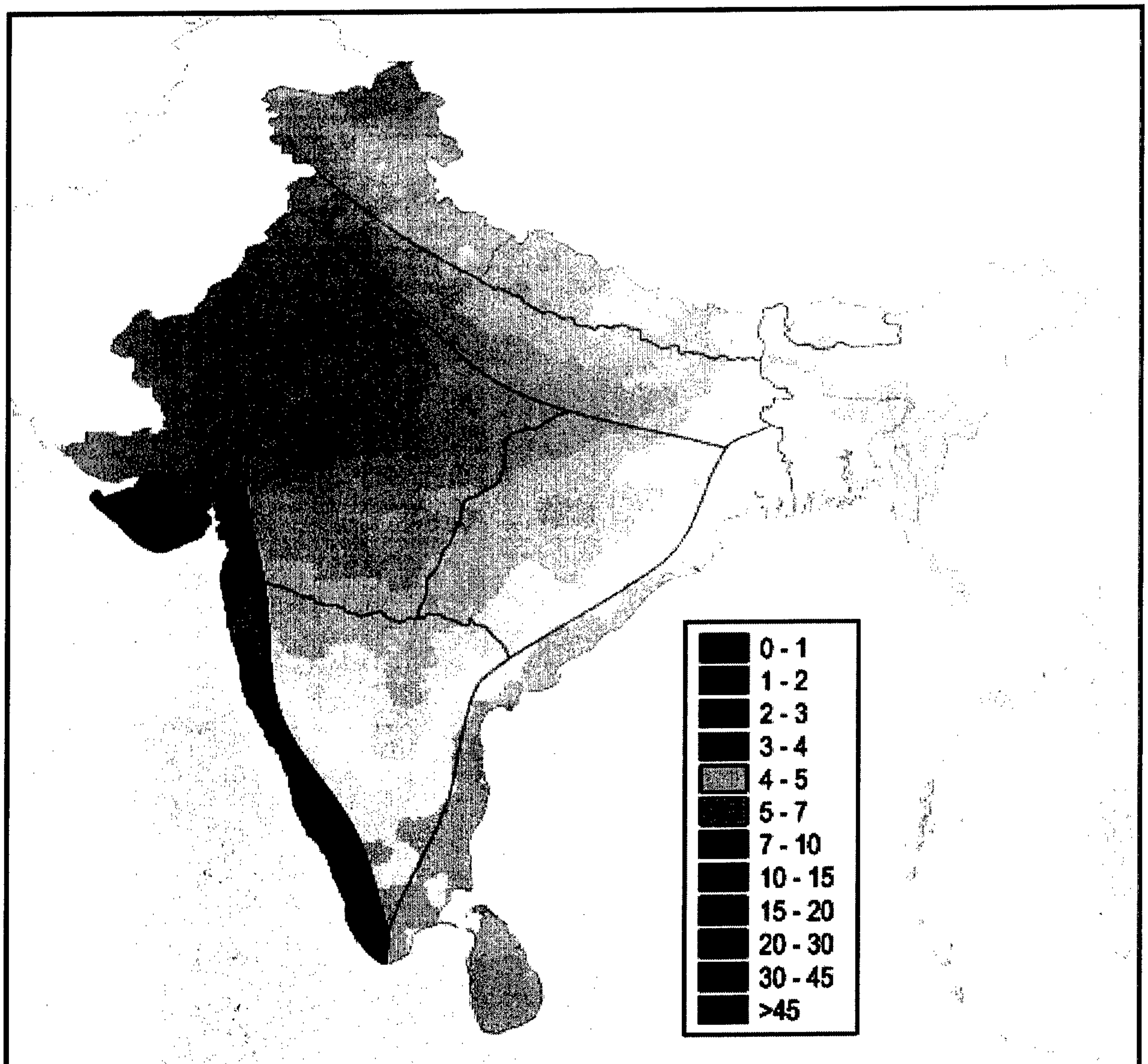


Figure 5-31. October Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

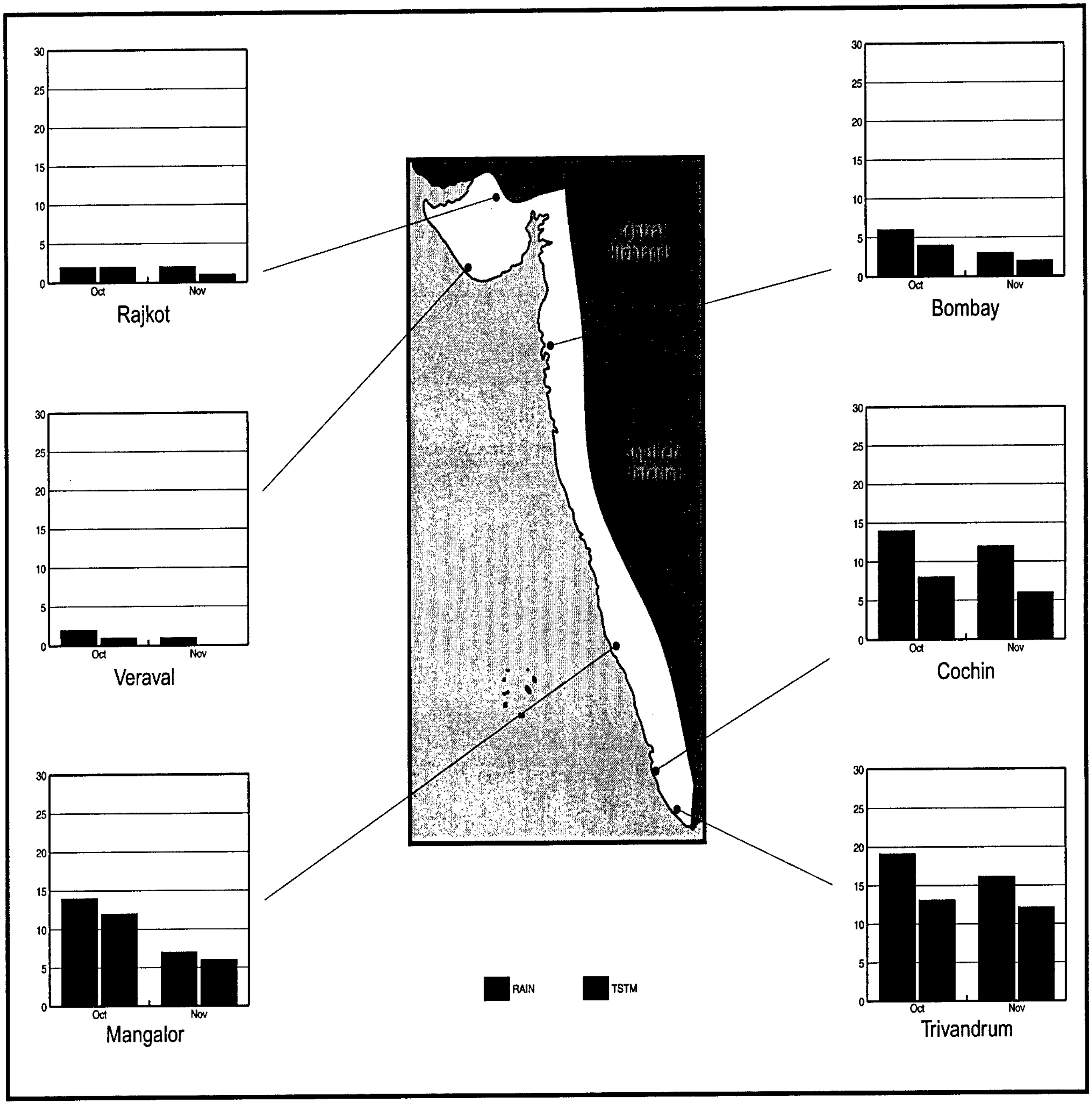


Figure 5-32. Post-Monsoon Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. As the cloudiness and rainfall decrease sharply, higher temperatures return. The southern stations, still in the southwest monsoon air flow, are not as hot as the rest of the coastal plains. Mean highs are 88° to 95°F (31° to 35°C) in October. The highest readings are at stations on the Kathiawar Peninsula. From Bombay south, mean highs are 85° to 90°F (29° to 32°C) in both months. Mean lows are 72° to 76°F (22° to 25°C). The coolest temperatures are in the northwest, near the Thar Desert, at night. All stations have recorded extreme highs of 100°F (38°C) or higher. Rajkot and Veraval recorded 109°F (43°C) in October. Extreme lows are 52° to 68°F (11° to 20°C). Figures 5-33 and 5-34 show the October mean high and low temperatures, respectively.

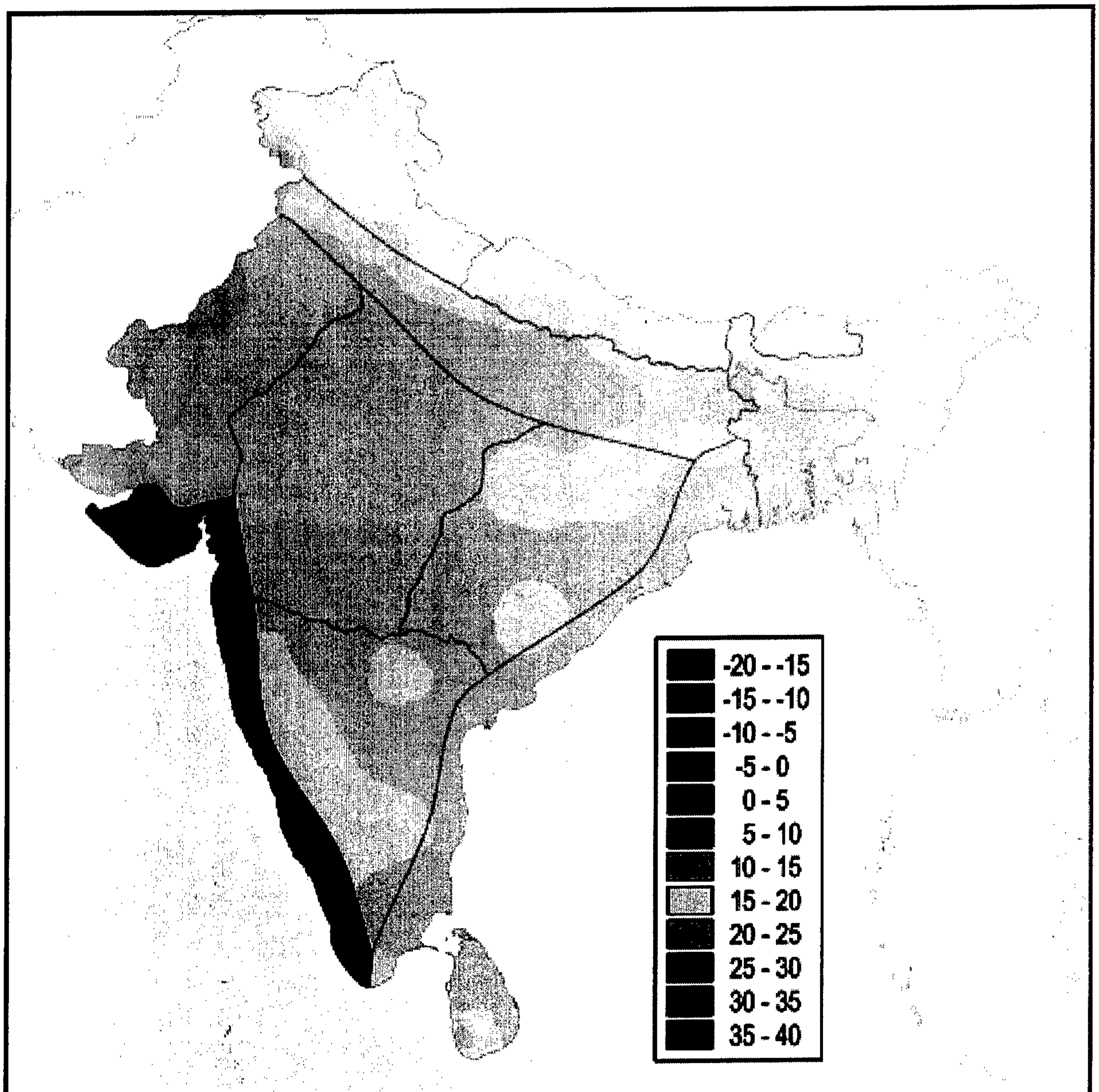


Figure 5-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for the month. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other months may be lower, especially at the beginning and ending of the season.

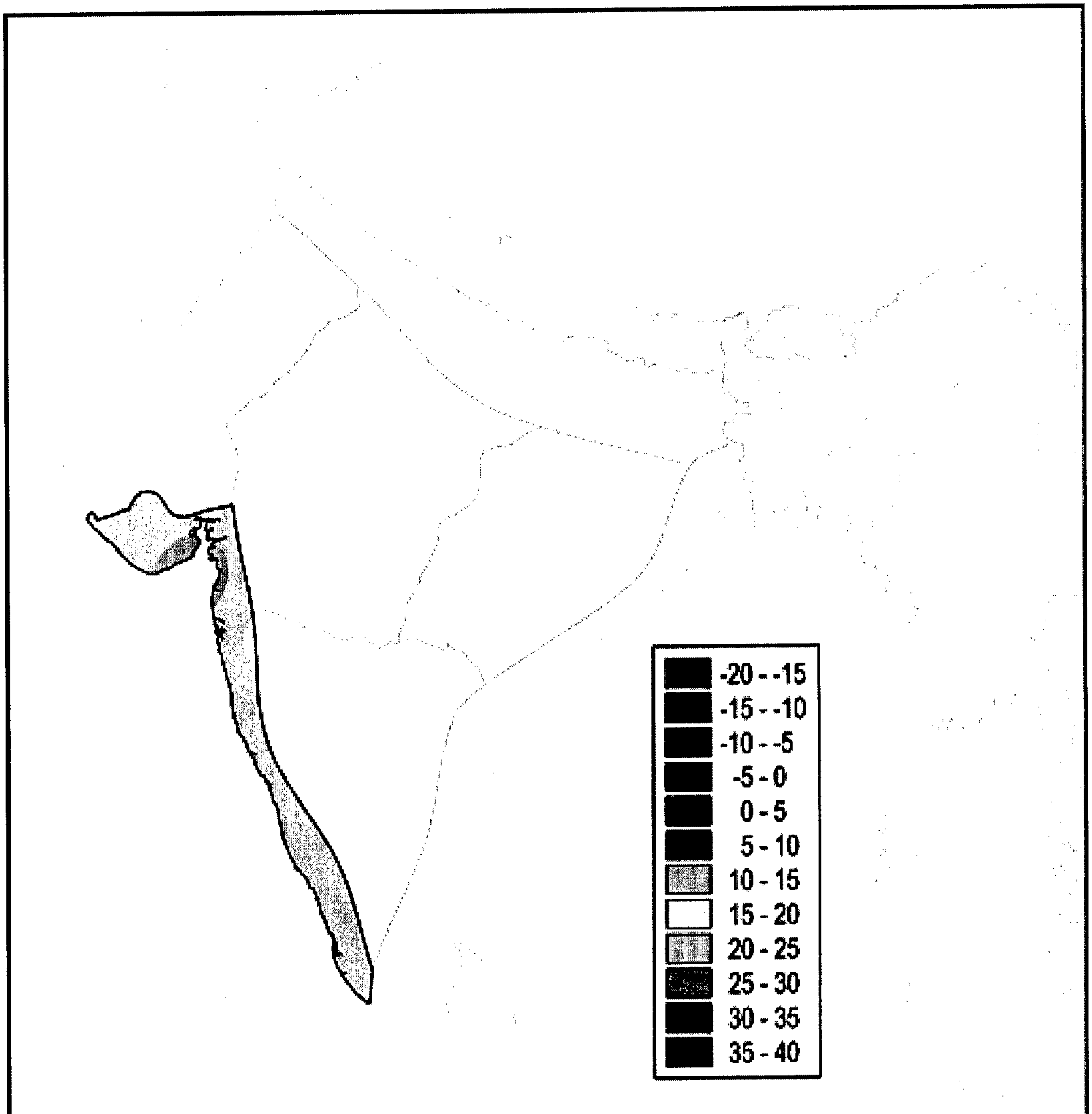


Figure 5-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for the month. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other months may be higher, especially at the beginning and ending of the season.

Chapter 6

CENTRAL HIGHLANDS

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for the Central Highlands of India.

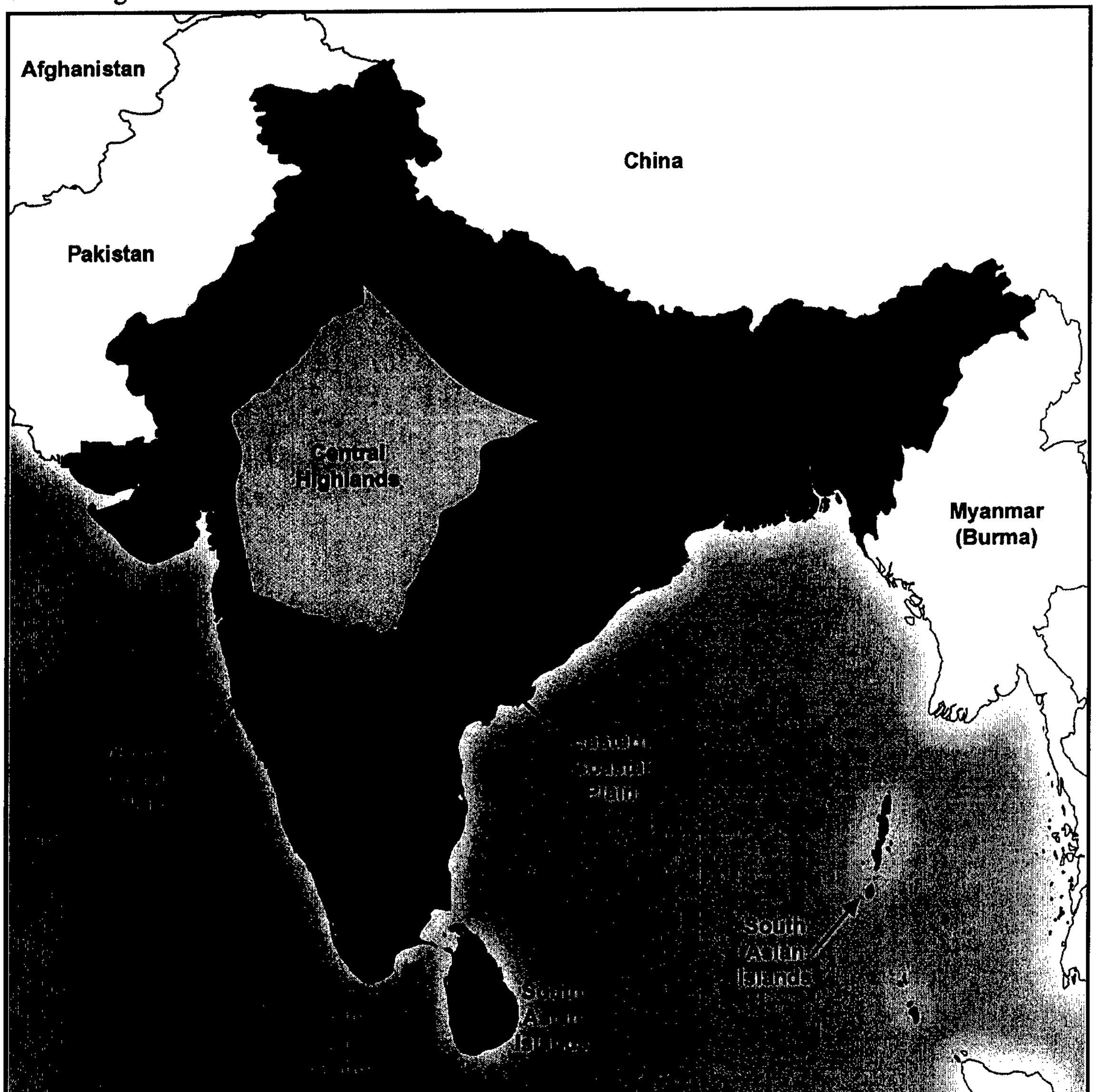


Figure 6-1. Central Highlands. The area in yellow depicts the Central Highlands.

List of Topics

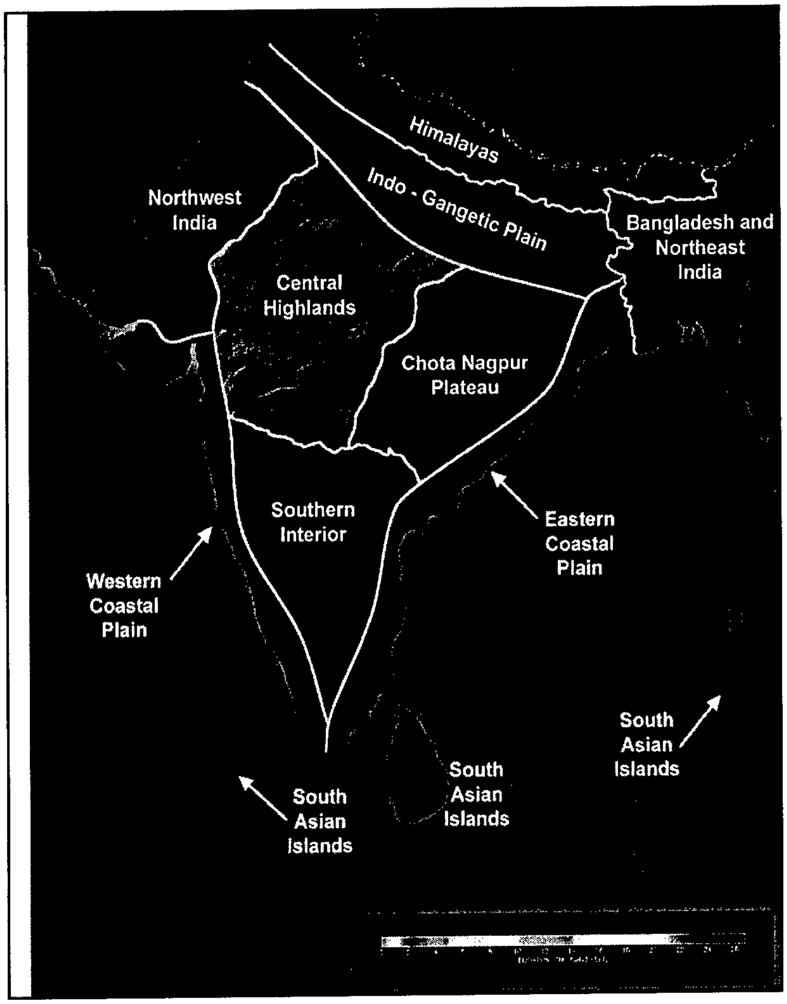


Figure 6-2a. Topography of the Central Highlands.

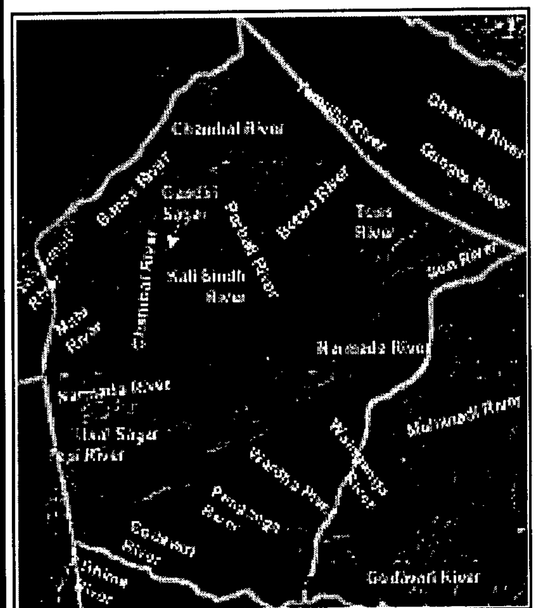


Figure 6-2b. Expanded View of Topography of the Central Highlands.

Topography

Area. The Central Highlands region is bounded by the Indo-Gangetic plain to the north, the Aravalli Range to the northwest, the Western Ghats to the west, and the Godavari River to the south. The eastern boundary runs along the Son River on the western rim of the Chota Nagpur plateau, then along the Narmada River westward to 80°E, then southward with the Wainganga and Pranhita Rivers along 80° E to the Godavari River.

General Topography. The region presents a confused amalgam of lowland and upland topography. The Central Highlands constitute the northern extension of the peninsular plateau. It has a series of west-east mountain ranges of moderate elevations, which reach to the southern margins of the Indo-Gangetic plains. The Vindhya Range, which stretches nearly the width of peninsular India, has an average elevation of 1,000 feet (300 meters). This range forms an important watershed, and along with the Satpura Range, constitutes the northern boundary of the Deccan plateau. The Satpura Range lies south of and parallel to the Vindhya Range. The Satpura Range is about 550 miles (900 km.) long, with elevations of 1,600-4,200 feet (500-1,300 meters). The Central Highlands separate the peninsular plateau from the Indo-Gangetic plains.

The northeast is guarded by Mount Abu and other outliers of the Aravalli. The east is bordered by hilly forest with spurs of the Vindhya and Satpura Ranges. The Sabarmati, Mahi, and Narmada Rivers contribute to the richness of the soil of the region.

The terrain is mainly forested hills with steep slopes, extensive plateaus, and river valleys. The Aravalli Hills are in the northwest. The southeastern Aravalli Hills are higher in elevation (330-1,150 feet or 100-350 meters, above sea level) and very diverse in character. To the east, the Bhorat plateau has an average elevation of 4,000 feet (1,225 meters). To the northeast of this area, rugged terrain follows the line of the Chambal River. Farther north, the country levels out to flat plains, part of the alluvial basin of the Yamuna (Yama) River.

The Deccan plateau and the Vindhya and Kaimur Ranges are in the center of the region. These two ranges rise to 1,500 feet (450 meters) above sea level in places. The Satpura, Mahadeo, and Maikala Ranges in the south have elevations of more than 3,000 feet (900 meters). Northwest of the Vindhya Range is the Malwa plateau 1,500-2,000 feet (450-600 meters).

The Western Ghats are an almost continuous range oriented 400 miles (640 km) north-south along the southwestern portion of the Central Highlands. They increase in elevation northward to peaks of some 4,700 feet (1,440 meters). There are a few gaps through which roads and railroads link the coast with the interior. The eastern slopes descend gently to the Deccan plateau and are sculpted by the wide, mature valley of the Godavari River. Between Narmada River valley in the north, Krishna basin in the south, and the western coast as far east as Nagpur, the Ghats and the triangular plateau inland are covered with extensive lava outpourings called "traps." The differential erosion of lava has resulted in characteristic step-like slopes, uniform crest lines, and the tabletop appearance of many hills. East of Nagpur, the Deccan Trap gives way to undulating uplands 900-1,000 feet (275-300 meters) high.

Rivers, Lakes, and Drainage Basins. The Central Highlands region contains numerous small lakes, streams, and rivers. The Gandhi Sagar and Ranh Prat Sagar are south of Kota along the Chambal River. Another major lake is the Rihand on the Chota Nagur plateau. The Aravalli Mountains form an important watershed, with the drainage from the east side of the range that flows northeast. The Chambal River is one of the major rivers of the Central Highlands. It flows northeastward and joins the Ganges. Its principal tributary, the Banas, rises in the Aravallis and collects the drainage of the Mewar plateau. Other large tributaries of the Chambal River are the Kali Sindh, Parwan Nadi, Parbati, Betwa, Ken, and the Tons Rivers.

The Satpura Range is the source region of some of the most important peninsular rivers, the Narmada, and the Tapi, which drain into the Arabian Sea, and the Wainganga (a tributary of the Godavari). The Western Ghats are the source of the Godavari River, which flows eastward along the slopes of the peninsula and drains into the Bay of Bengal. Other rivers include tributaries of the Yamuna and the Son Rivers. The Wardha-Wainganga valley, part of the larger Godavari basin, trends southward and abounds in lakes.

Major Climatic Controls

Asiatic High. This thermal high develops over Asia and dominates the weather over the entire continent from November to April. A vast pool of cold, dry air pushes outward in all directions and is a key part of the northeast monsoon in South Asia. Because of the continental source of the air, the weather is dry. The lee side trough on the southern side of the Himalayas created by flow out of this high provides a track for storms that move out of Europe on the subtropical jet.

Australian High. This thermal high sets up over Australia during Southern Hemispheric winter (May through October). It helps smooth the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ), which is a southwest monsoon feature. The outflow from this high also helps to push the equatorial trough (ET) northward to produce the southwest monsoon season (rainy season) in South Asia.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon (November to April). It forms during a cold outbreak and stabilizes the weather over the whole area, bringing clear-to-scattered skies, generally good visibility, and light winds. This high does two different things depending on its strength and position. Although always weak, when the high is at its strongest, it tends to block low pressure systems from the track across the southern foot of the Himalayas by displacing the lee-side trough that is typically in place. The farther north the high develops, the more likely it is this will happen. When the high is weakest, it tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline used by lows out of Europe that ride the subtropical jet to move rapidly across northern India. Western disturbances are enhanced when the Indian high is weak.

North Pacific High. This is a major player in the monsoon seasons of South Asia. It shifts north and west in Northern Hemisphere summer (May through October) and east and south in the winter (November to April). The high is linked to the position of the ET, which marks the boundary between the northeast and southwest monsoons.

South Indian Ocean (Mascarene) High. This year round high shifts north and south with the sun. At its strongest during Southern Hemisphere winter, it provides cross-equatorial flow from May to October. This warm, moist flow contributes significantly to the ET shift to the north, which brings the southwest monsoon to South Asia.

Asiatic Low. This is a thermal low that replaces the Asiatic high during Northern Hemisphere summer. The land heats and the consequent low draws in air. This contributes to the ET shift northward, which brings the southwest monsoon flow to South Asia.

Australian Low. This is a thermal low that develops over Australia in Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the Bay of Bengal and is a southwest monsoon feature (May to October). Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for the development of monsoon depressions.

Monsoon Climate. For South Asia, the monsoon climate means the subcontinent has a distinct rainy season and dry season. Under the northeast monsoon (November to April), the region is largely dry. Under the southwest monsoon (May though October), it is rainy. Onset of the rainy season varies by latitude and terrain, but it usually occurs between mid May and late June. Duration of the rainy season also varies widely. In the north, the southwest monsoon season is short; in the far south, it often lasts twice as long as in the far north.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north (May through October), the southwest

monsoon takes over in South Asia. When it shifts south (November through April), the northeast monsoon assumes control. Chapter 2 offers more details.

Bay of Bengal. This large bay is the primary breeding ground for tropical cyclonic storm systems that affect this region. Most of the rainfall in this area occurs with storms that develop or refire over this body of water along the ET, the India-Myanmar trough, or from other mechanisms. The northern half of the bay is more active than the southern half, but storms develop here year round. The most active times are in October-November (maximum activity) and April-May (secondary maximum). Storms tend to come ashore on the east coast of the peninsula then recurve northward.

Special Climatic Controls

Tropical Easterly Jet (TEJ). This jet exists only during the southwest monsoon season (May through October). An upper- level jet that overlays the low-level westerlies, it provides an outflow mechanism for disturbances that develop below it. The heaviest precipitation in South Asia occurs directly beneath the TEJ. The Bay of Bengal and the Arabian Sea are both under the TEJ. The Bay of Bengal is well known to be a prime area for the development/regeneration of monsoon depressions, tropical cyclones, tropical waves, tropical vortices, and mesoscale convective complexes. The TEJ is an important element in the process.

Somali Jet (Low-Level Jet). Also known as the East African low-level jet, this jet exists during the southwest monsoon season and is a key transport for air from the Southern Hemisphere into the Northern Hemisphere. It is thought 50 percent or more of the cross-equatorial flow from the Southern Hemisphere into the Northern Hemisphere is moved by this jet. It is created when outflow from the South Indian Ocean high flows toward the thermal low pressure over northern Africa (May through October). The western edge of the outflow air mass compresses against the eastern slopes of the high mountains of the eastern African coast. The result of this squeeze is a terrain-induced zone of tight pressure gradient, and the jet develops there. The Somali jet is a key element in the development of the equatorial westerlies that dominate the southwest monsoon season.

Equatorial Westerlies. These winds exist during the southwest monsoon season. These large-scale, low-level winds are a result of a combination of factors. Outflow from the South Indian Ocean high (from the southeast) flows toward the thermal low over northern Africa (to the northwest), but the high mountains on the eastern coast of Africa are significant barriers that force a deflection. The Somali jet then helps transport the air into the northern hemisphere. The air mass is recurved eastward and these westerly winds take over throughout the monsoon region.

Subtropical Jet (STJ). This jet is significant in this region in the northeast monsoon season (November to April) when its southern branch slips south of the Himalayas. Low pressure systems out of Europe (western disturbances) ride the jet through the northern part of India, Bangladesh, and East India. During the southwest monsoon, the SJT is north of the Himalayas.

Western Disturbances. These develop from short waves in the larger, long-wave pattern. They move from west to east and are often most easily observed at 500 Mb. In South Asia, particularly in winter (November through April), several waves move across the northern portions of the subcontinent and give rise to cloudiness and precipitation. The STJ, south of the Himalayas in winter, provides transport to rapidly move theses waves into and through the area.

Tibetan Anticyclone. This Northern Hemisphere, southwest monsoon upper-air feature sets up in the zone between the deep easterlies that reach almost to the foot of the Himalayas by July and the deep westerlies of the Northern Hemisphere midlatitudes. Formed above the thermal low of the Tibetan plateau, it is important to the climate during this season because tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. Also, since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought. For detailed descriptions, review Chapter 2.

Easterlies. This deep east wind band persists year round in the low latitudes. It shifts north and south with the

sun. During the southwest monsoon, it shifts north and widens to encompass a larger area. Thanks to a number of factors, it also strengthens enough to develop the tropical easterly jet, a broad ribbon of higher winds that strongly influence the development of monsoon rains, tropical disturbances of all intensities, and monsoon depressions. During the northeast monsoon, the band of easterlies narrows and shifts south. At the height of the northeast monsoon, the easterlies are held south of 5° N.

Easterly Waves. During the southwest monsoon season (May through October), easterly waves are known to help fire the formation of monsoon depressions over the northern Bay of Bengal. They travel from east to west in the deep easterlies and last 1-2 weeks. They are accompanied by clear weather ahead of the trough and heavy showers and thunderstorms behind. They sometimes create cyclonic vortices off shore the southwestern end of the Indian peninsula and can cause thunderstorms and rainshowers over Sri Lanka and the southern tip of the peninsula. The intensity and frequency of occurrence of easterly waves are indicators of the strength of the monsoon.

Cyclonic Storms. Monsoon depressions, tropical cyclones, tropical waves, tropical vortices, mesoscale convective complexes, and cloud clusters are types of cyclonic storms of varying scales of intensity and size. Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Some travel into the area from the west (western disturbances). Some of these factors have influence during the southwest monsoon season, such as the Tibetan anticyclone, easterly waves and the India-Myanmar trough. The ET influences the weather during the transition periods when it moves through the area. During the northeast monsoon, western disturbances and tropical vortices are the bigger players in the development of weather systems. Regardless of when they develop, some storms can be fierce. Because the waters of the Bay of Bengal are so confined, however, storms do not have the opportunity to develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation to the shores of India and Bangladesh, cause extensive flooding and loss of life, and destroy crops and property. Storms tend to come ashore on the peninsular east coast of India then recurve northward. The heaviest precipitation falls in the southwest through south quadrants of the storms. May, October and November are the months when the most intense cyclones develop. The months of October and November witness the most severe cyclonic storms. The tracks of the storms are found to vary considerably between El Niño and La Niña years.

Mid-Tropospheric Cyclones. Mid-tropospheric cyclones develop during the southwest monsoon near the 600 mb level. They occur most frequently in the northeastern Arabian Sea and are a major producer of rain on the west coast plains of India. A weak trough along the northwest coast is often the only indication of a surface disturbance. The cyclones produce wide-spread layered clouds, imbedded thunderstorms, and heavy precipitation--8 inches (203 mm) in 24 hours. The systems last 9-10 days and are essentially stationary.

Monsoon Depressions/Low-Pressure Systems. These are important synoptic-scale disturbances that make major contributions to the monsoon circulation in organizing low-level convergence. During the southwest monsoon season, these storms move along the ET (monsoon trough) toward the north. They normally form in the Bay of Bengal north of 18° N and move west-northwest across India. They bring heavy rains, especially in the southwest quadrant of the storm. These systems rarely develop into tropical cyclones and are associated with a series of low-pressure systems and easterly waves in the northern Bay of Bengal. The strongest winds are in the southern sector of the storms thanks to augmentation by the equatorial westerlies. Approximately 80 percent of the total number of depressions that form in the South Asia region are monsoon depressions. The majority of monsoon depressions and other cyclonic storms form in the Bay of Bengal as opposed to the Arabian Sea and most of them form in the northern part of the bay.

Land/Sea Breeze. These winds are caused by diurnal land/sea temperature differences. By day, the sea is cooler than land and the wind blows onshore. By night, the temperature difference reverses and the winds become offshore. Onshore winds produce cloud cover and convection over land. During the southwest monsoon, sea breeze winds are augmented by the large scale flow and reach far inland, as much as 100 miles (160 km). This brings moist air well inland to rise up mountain slopes and cause precipitation in the mountains. Offshore winds clear the skies over land by pushing cloud cover out to sea. These same winds can slide convection that developed over the mountains down into the lowlands between them and the sea. Depending on the steepness of the slopes, the downslope flow can create a "front" that fires thunderstorm activity all along the convergence zone between the cool mountain air and the warmer, moist air of the sea. This makes up a line of thunderstorms that marches to the sea over the lowlands.

Hazards for All Seasons

Turbulence. Under the clear-to-scattered skies of winter and the hot season, turbulence caused by intense surface heating may reach 10,000 feet. The turbulence is usually light-moderate but can be severe. Some low-level turbulence is almost always present during the afternoons, but is most likely during the hot season and with thunderstorms. Convective currents are most pronounced between 1000 and 1700L. During the southwest monsoon, turbulence is primarily associated with convective currents and thunderstorms; during the winter, turbulence is mostly with fronts. Moderate to severe turbulence occurs with the STJ at 35,000-40,000 feet during the winter and hot seasons. During the southwest monsoon, moderate to severe turbulence occurs near the TEJ at 40,000-45,000 feet.

Icing. The mean freezing level is 14,000 feet in the winter and 16,000 feet during the southwest monsoon. The mean height of the -20° C isotherm is 23,000 feet in winter and 26,000 feet during the southwest monsoon. Consequently, icing can only occur with thunderstorms.

Thunderstorms. During the winter and early hot season, thunderstorms develop along the cold fronts that often accompany western disturbances as they move across central India. All of these storms may produce torrential rain, strong wind gusts, violent up and down drafts, turbulence, icing, lightning, and in-cloud hail. Hail seldom reaches the ground; if it does it is usually small, soft, and causes little damage. Thunderstorms also accompany the ET.

Flash Floods. Incredible amounts of rain fall in a very short time during the southwest monsoon. Streams and rivers overflow their banks. Flash floods occur quickly with little or no warning.

Heat. High temperatures and humidity create a wide variety of heat-related physical problems. The wet-bulb globe temperature averages 80°F (27°C) in January, and increases to greater than 90°F (32°C) by July.

Tropical Cyclones. Tropical cyclones occur any month of the year, but are least frequent from January through March. In April and May, these storms are still relatively infrequent, but those that do appear are apt to develop and become severe. Arabian Sea storms, on rare occasions, recurve northeast and strike the Rann of Kutch coast and move into the Central Highlands region to cause widespread devastation in heavy rains and floods. At the height of the southwest monsoon, a series of lows form in the Bay of Bengal and travel westward or northwestward over land. They sometimes die out over the interior, but reactivate over north-central India where they meet the fresh monsoon air from the Arabian Sea.

Winter

General Weather. Throughout winter, India is under light, northerly flow that originates from the Asiatic high in the north. The Himalayas block the bitterly cold air from India, thus a weak pressure gradient associated with the Asiatic high prevails. The weak outflow associated with the Asiatic high warms before it reaches South Asia. The North Pacific high keeps the equatorial trough (ET) well south of India during the winter. Migratory lows driven by the subtropical jet cross the northern part of India. India becomes influenced by the westerly flow, and occasional westerly disturbances. These weak perturbations can sometimes produce winter rains and isolated thunderstorms. Toward the end of winter, India begins to receive weak tropical waves, an increase in convective activity, and infrequent occurrences of tropical depressions. The ET generally moves erratically depending on the strength or weakness of the dominating high-pressure systems.

Modified continental polar air masses produce cool days, cold nights, and low humidity. The sky is generally clear with occasional high cirrus; winds are light to moderate, and visibility is generally good. During its southward progression, the air absorbs heat from the surface. Stability decreases as it moves away from the influence of the Asiatic high.

Tropical depressions, which happen to cross the region, generally produce copious amounts of rain. Floods can occur around river basins and other low lying areas. Severe thunderstorms and high winds of 35 knots or greater are generally associated with these depressions.

Sky Cover. Winter cloudiness is predominantly middle and high cloud, mainly altocumulus and cirrus. Limited cumulus clouds develops at times over the region during the afternoon and dissipate again near sunset. Thunderstorm bases average 4,000 feet while tops near 30,000 feet. In the early mornings over the river valleys, low stratus may develop but rapidly dissipates soon after sunrise. Ceilings at any level occur less than 20 percent of the time. The average occurrence rate of ceilings below 3,000 feet is 6 percent or less throughout the entire region (see Figure 6-3). Ceilings below 1,000 feet occur less than 3 percent in most areas. Most low ceilings occur between 0000Z and 1200Z.

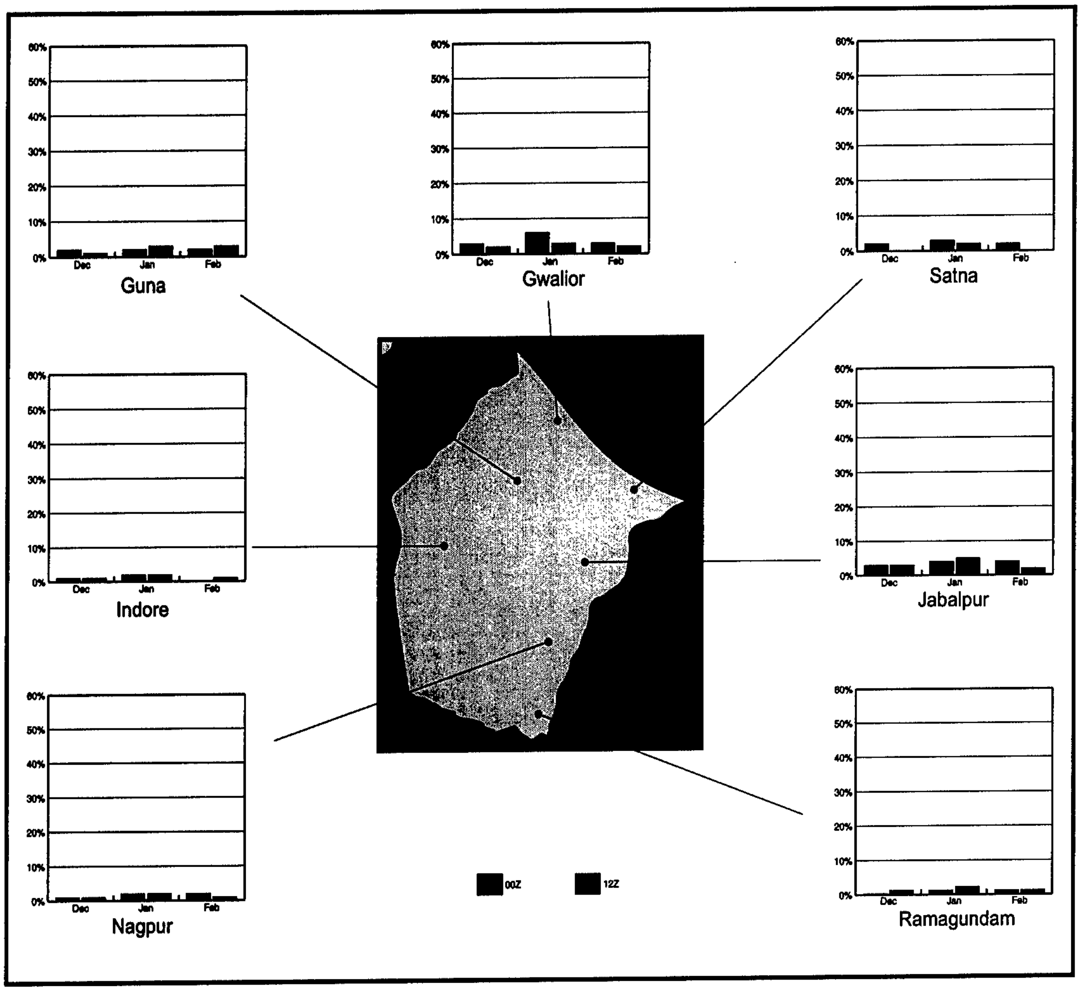


Figure 6-3. Winter Percent Frequency of Ceilings below 3,000 Feet. The graphs show a monthly breakdown of the percentage of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. Topographic features and local conditions are of paramount importance in the determination of visibility. In the morning, visibility is generally far worse than in the afternoon. In industrial areas, visibility will be reduced in smoke, which is worst at night and early mornings. Smog is common in the morning hours in industrial cities. Diurnal variation is much greater in winter than in any other season. The principal restrictions to visibility are fog, dust, smoke, and haze. Fog is the most frequent in winter as a result of nocturnal cooling. River valleys experience a greater frequency of fog. In these areas, it occurs mostly during the early morning hours. The height to which fog extends varies from shallow ground fog to about 1,000 feet (300 meters) in upslope fog along the Vindhya and Satpura Ranges. The most fog occurs along the Vindhya Range. There, radiational fog usually occurs in the early morning hours and dissipates by mid-morning, an average duration of 3-5 hours. Dust or sand storms can occur in winter, particularly in the northern areas of the region. Smoke and haze become significant toward the end of winter due to frequent brush fires.

Visibility less than 3 miles (4,800 meters) occurs less than 15 percent of the time throughout much of the region (see Figure 6-4). In and around major industrial centers, occurrences of visibility less than 4,800 meters increase to 20-25 percent of the time. Nagpur experiences visibility less than 4,800 meters as much as 51 percent of the time during the winter. This drastic difference is primarily due to its location. Nagpur is a fairly large, industrial city in a valley; the city's pollution becomes trapped below the inversion and creates poor visibility for long periods of time. New Delhi, although north of the region, produces a massive amount of pollution in it as northwesterly winds blow pollution and a swath of lower visibility southeast down the river valley. Gwalior, for instances, experiences a very high frequency of visibility below 4,800 meters. This is the result of the northwesterly flow of air which transports an abundance of smoke and other pollutants from New Delhi. Visibility less than 1/2 mile (800 meters) is rare everywhere.

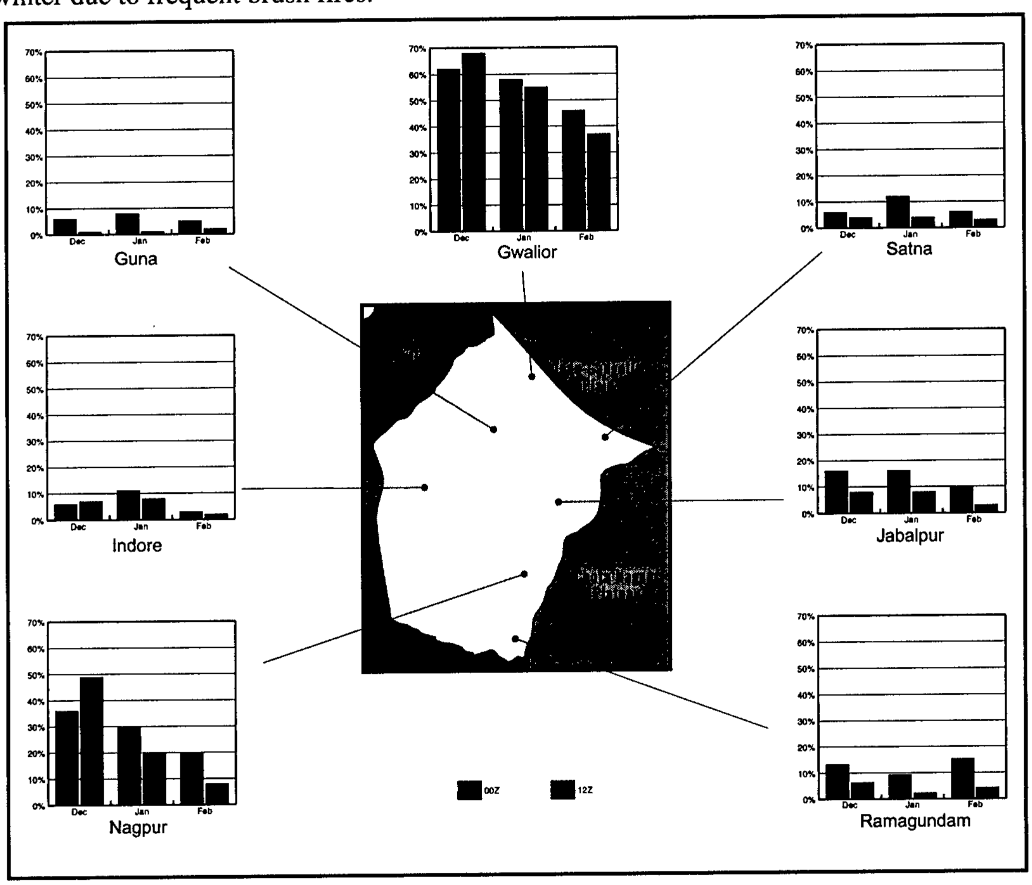


Figure 6-4. Winter Percent Frequency of Visibility below 3 Miles (4,800 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,800 meters based on location and diurnal influences.

Surface Winds. The prevailing winds are northerly. During the winter, it is extremely rare for winds to exceed 25 knots. The widely varied terrain plays a significant role in determining wind direction as seen in wind roses for selected Central Highlands locations in Figure 6-5. The winds in the north are northwesterly or northeasterly at 5-7 knots during the afternoon. In the evening, conditions are calm more than 40 percent of the time. In the south, winds are slightly stronger. During the evening, winds are northeasterly at 10 to 12 knots, and during the day, they are southeasterly at 10-15 knots. With increased solar radiation, the winds become gradually stronger, with a greater frequency of southwesterly winds with the approach of the hot season. With the stronger winds, dust storms occur. Dust storms occur once a month on average in the northern areas of the region as strong winds pick up large quantities of sand and dust from the Thar Desert and distribute it downstream. In the southern part of the region, dust storms occur less than once a month.

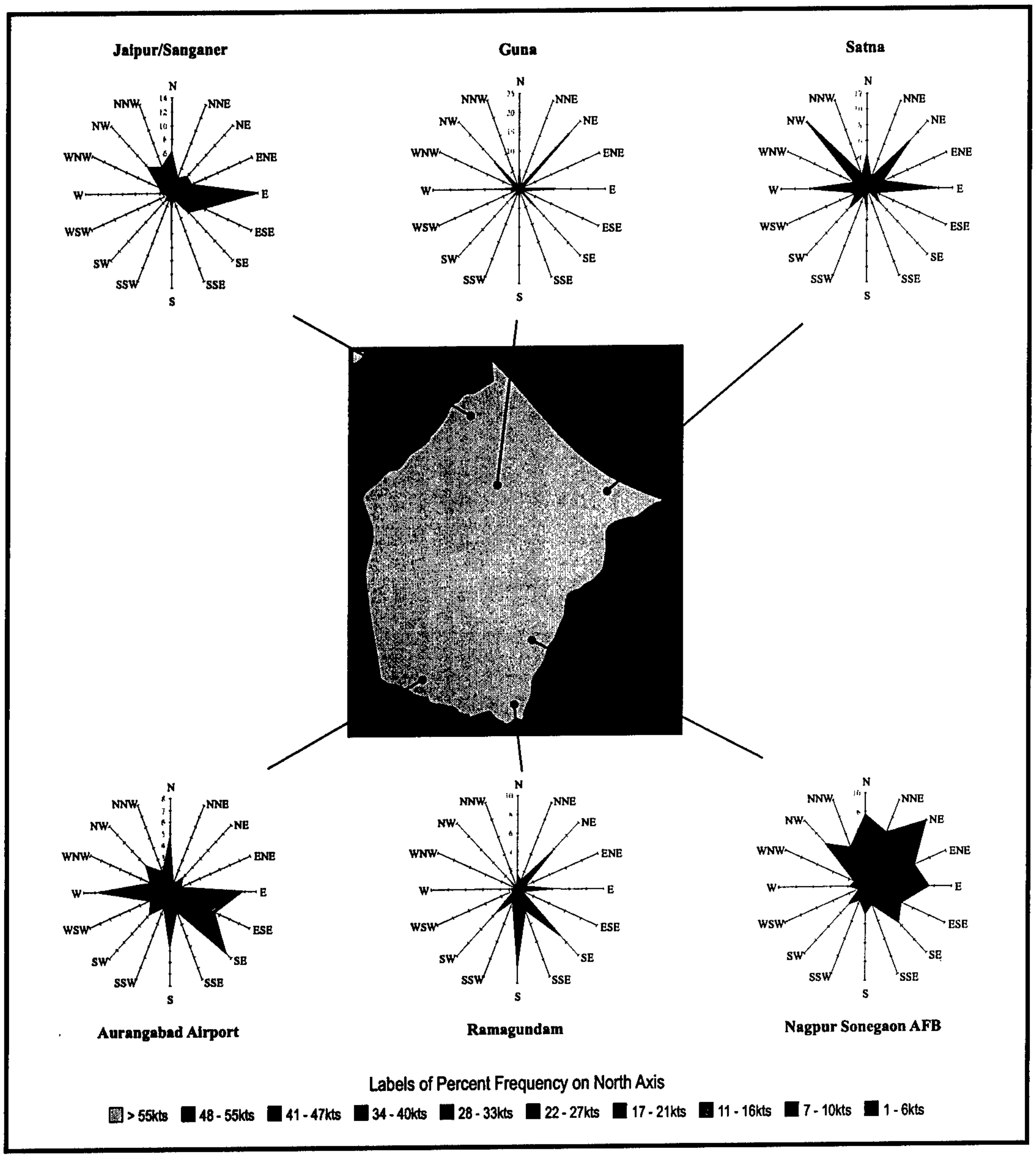


Figure 6-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper -Air Winds. Wind directions vary with latitude as well as height. The prevailing westerlies reach maximum strength in the winter. Westerly flow prevails above 10,000 feet. Below 10,000 feet, winds are light and mostly from the west-northwest. Below 700 mb, westerly winds gradually strengthen from December to February. At 500 and 300 mb, westerlies dominate; December winds at 300 mb average 60-90 knots; by February, speeds of 120 knots occasionally occur. This reflects the southern periphery of the subtropical jet; the core is usually near 200 mb over the southern edge of the Himalayas. Figure 6-6 shows the upper-air winds typicallly found at Aurangabad and Bhopal in January.

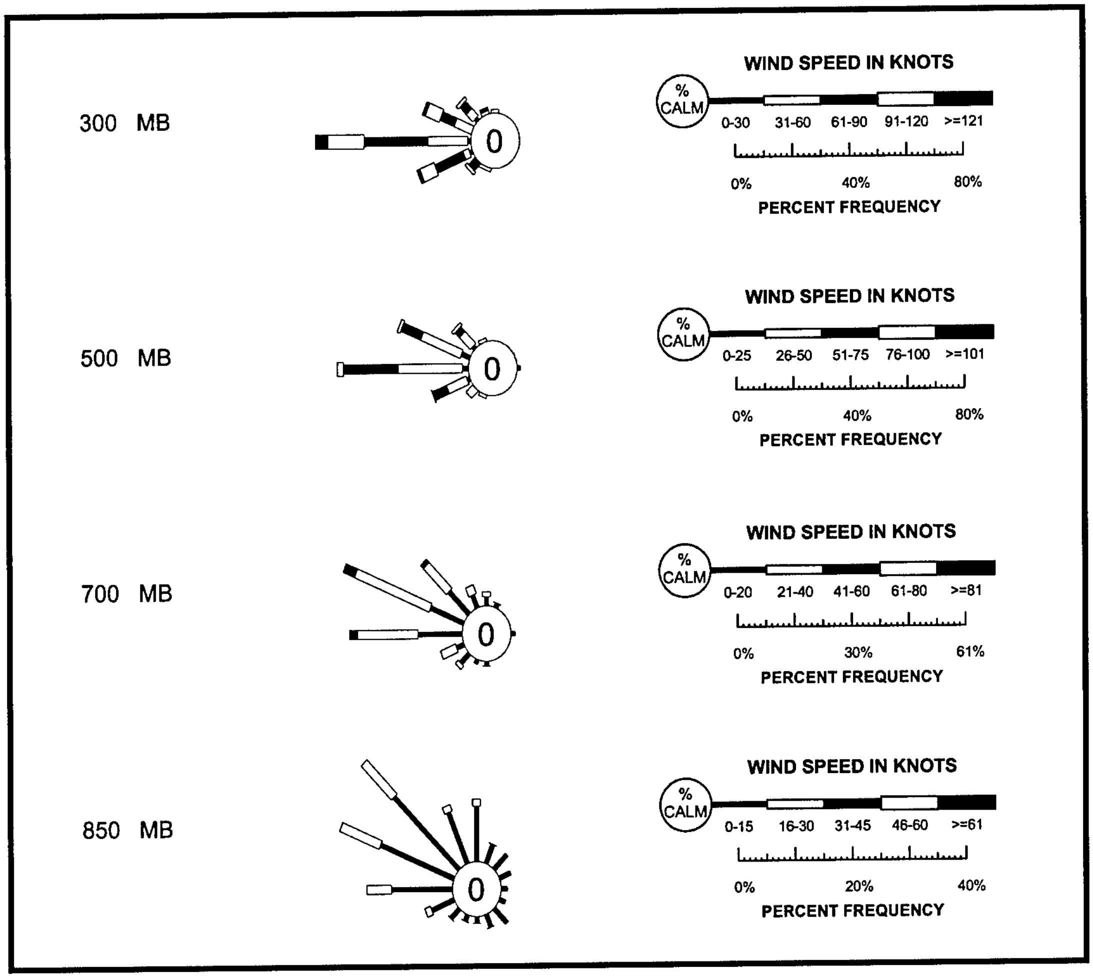


Figure 6-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Aurangabad and Bhopal.

Precipitation. The winter precipitation over the Central Highlands is a small part of the average annual amount. Terrain plays an important role in determining the distribution of precipitation. Immediately east of the western Ghats, the rainfall is sharply lower (rain shadow) than the rest of the region. The Satpura, Vindhya, and Aravalli Ranges are not significant barriers to precipitation. The average rainfall throughout the region is less than 1 inch (25 mm). At the eastern base of the Western Ghats, the average precipitation is 0.2 inch (5 mm). The amounts increase from west to east, with accumulations of 0.8 inch (20 mm) along the eastern most reaches of the region. The average number of days with precipitation is 2-3 per month along the western edge, and 4-5 per month in the east. Maximum 24-hour precipitation averages 2 inches (51 mm), and on extremely rare occasions, can be as much as 4 inches (102 mm). Thunderstorms are rare; 1-2 occur at most stations during the season, except at Satna, where as many as 3 occur each month. Hail occurs approximately once every 5 years during the winter months. Figures 6-7 and 6-8 show January mean precipitation amounts and seasonal precipitation and thunderstorm days, respectively.

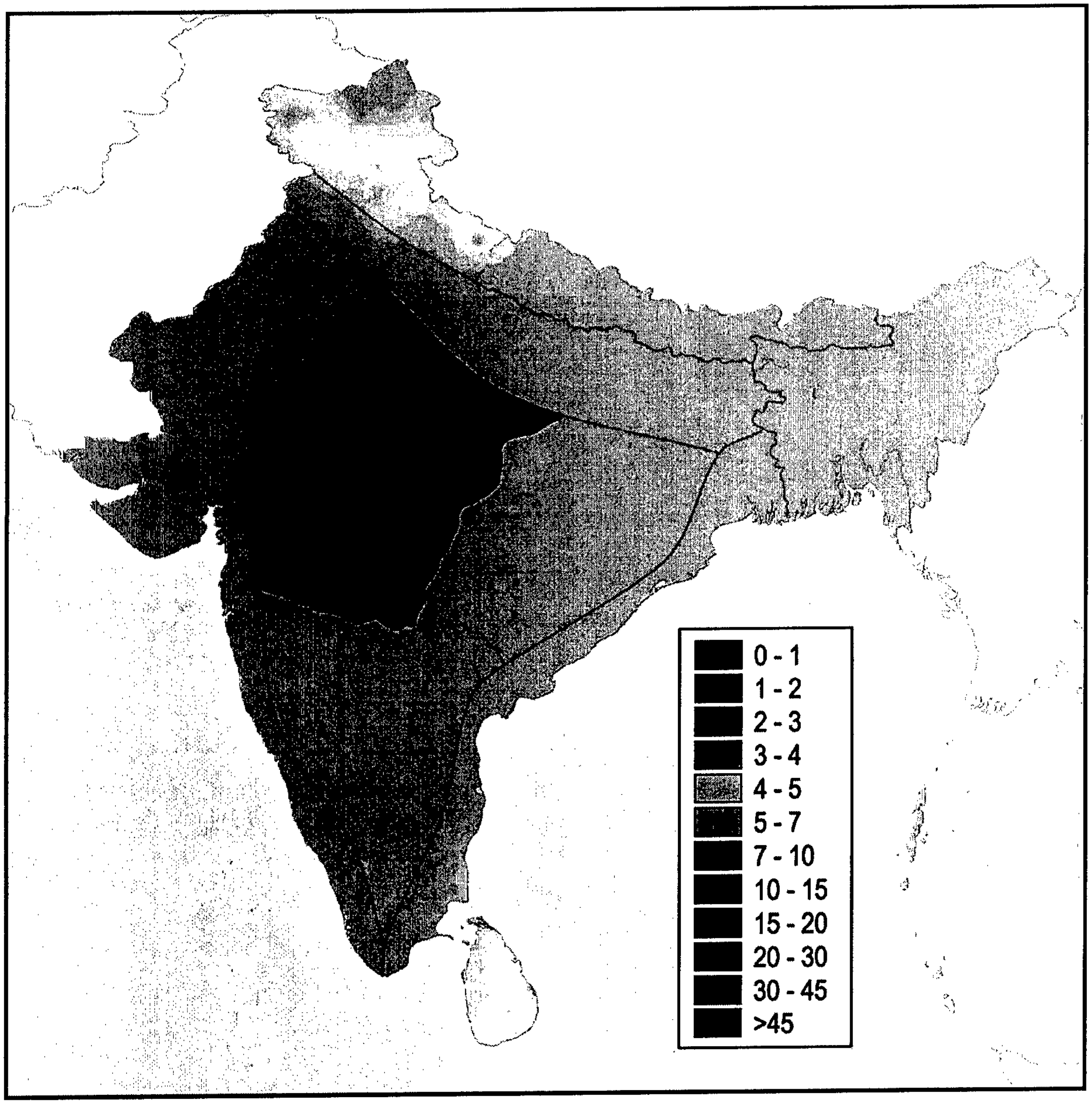


Figure 6-7. January Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

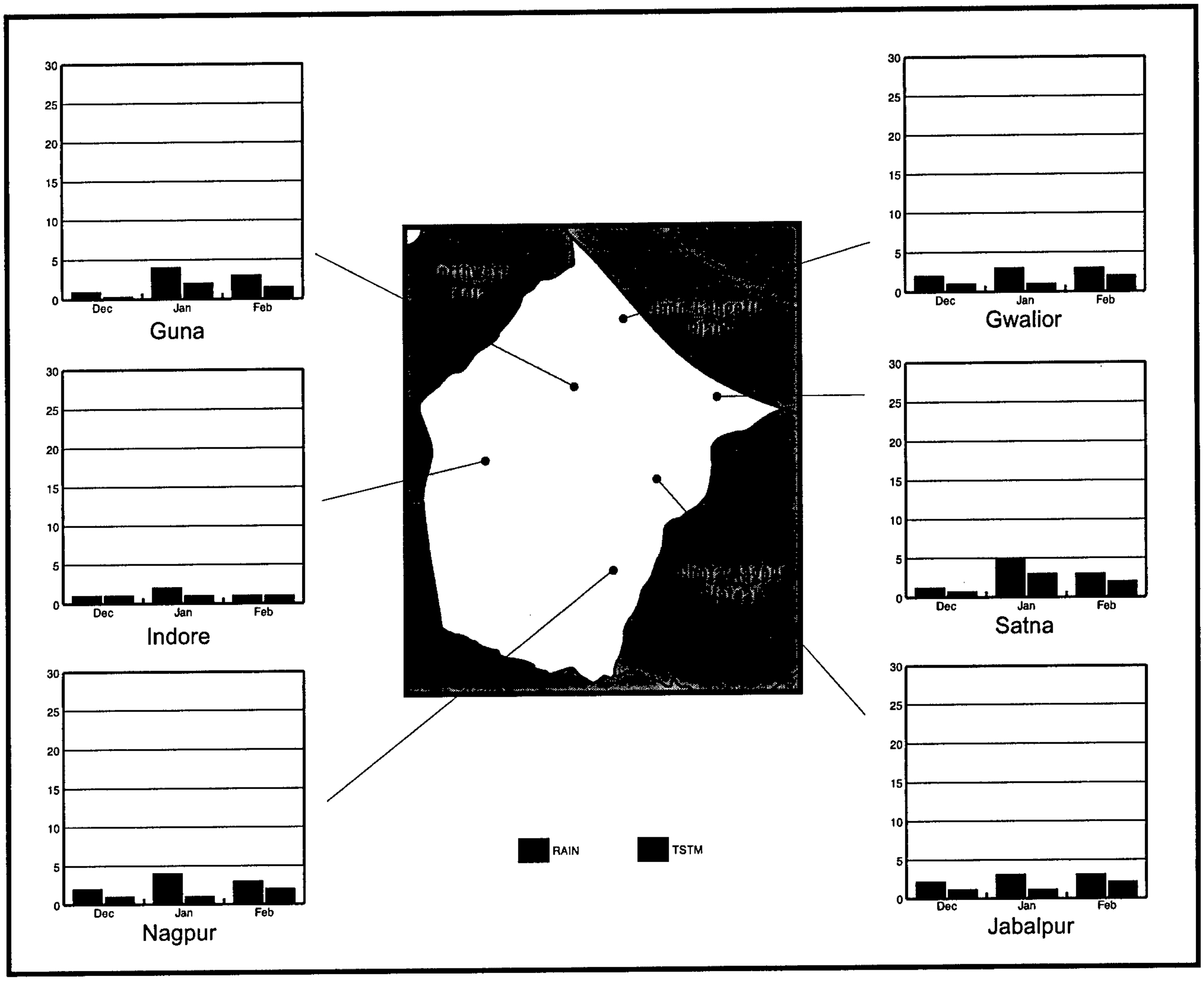


Figure 6-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. The mean maximum temperatures range from 82° to 87°F (28° to 31°C) in the south to 75° to 79°F (24° to 26°C) in the north. Mean minimum temperatures are 57° to 62°F (14° to 17°C) in the south, and 45° to 50°F (7° to 10°C) in the north. The mountains in northwest India and Pakistan are very much lower than the massive Himalayan ranges. During cold outbreaks from the Asiatic high, cooler air flows over these low mountains from the northwest and brings lower temperatures. Extreme lows generally range from 32° to 36°F (0° to 2°C) to the north to 36° to 40°F (2° to 4°C) in the south. Freezing temperatures are very rare. Although this is the coolest time of the year, extreme highs occasionally reach 100°F (38°C) or higher throughout the area. The highest temperatures occur just to the east of the Western Ghats. Figures 6-9 and 6-10 show the January mean maximum and minimum temperatures, respectively.

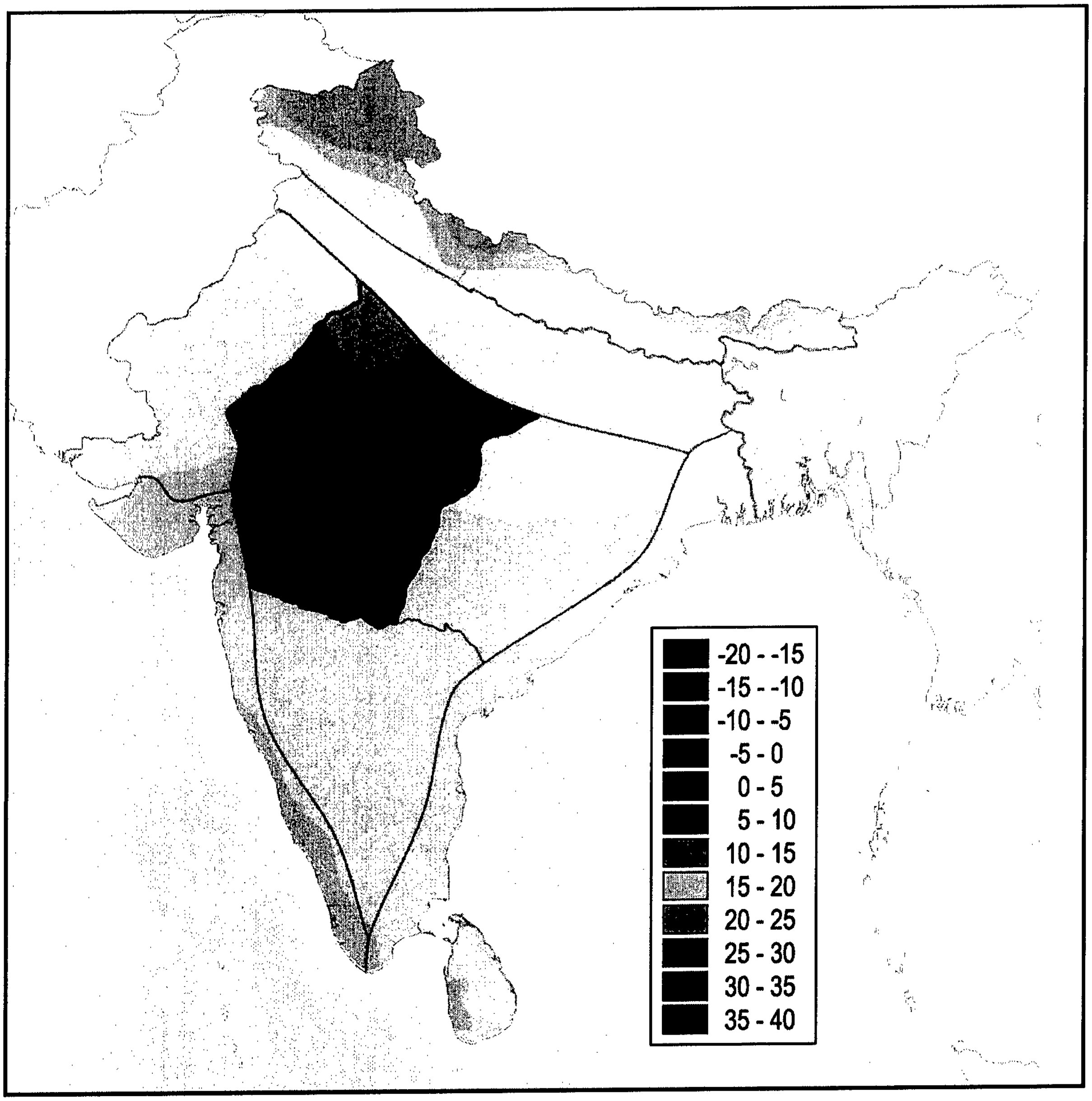


Figure 6-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for January. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other winter months may be higher, especially at the beginning and ending of the season.

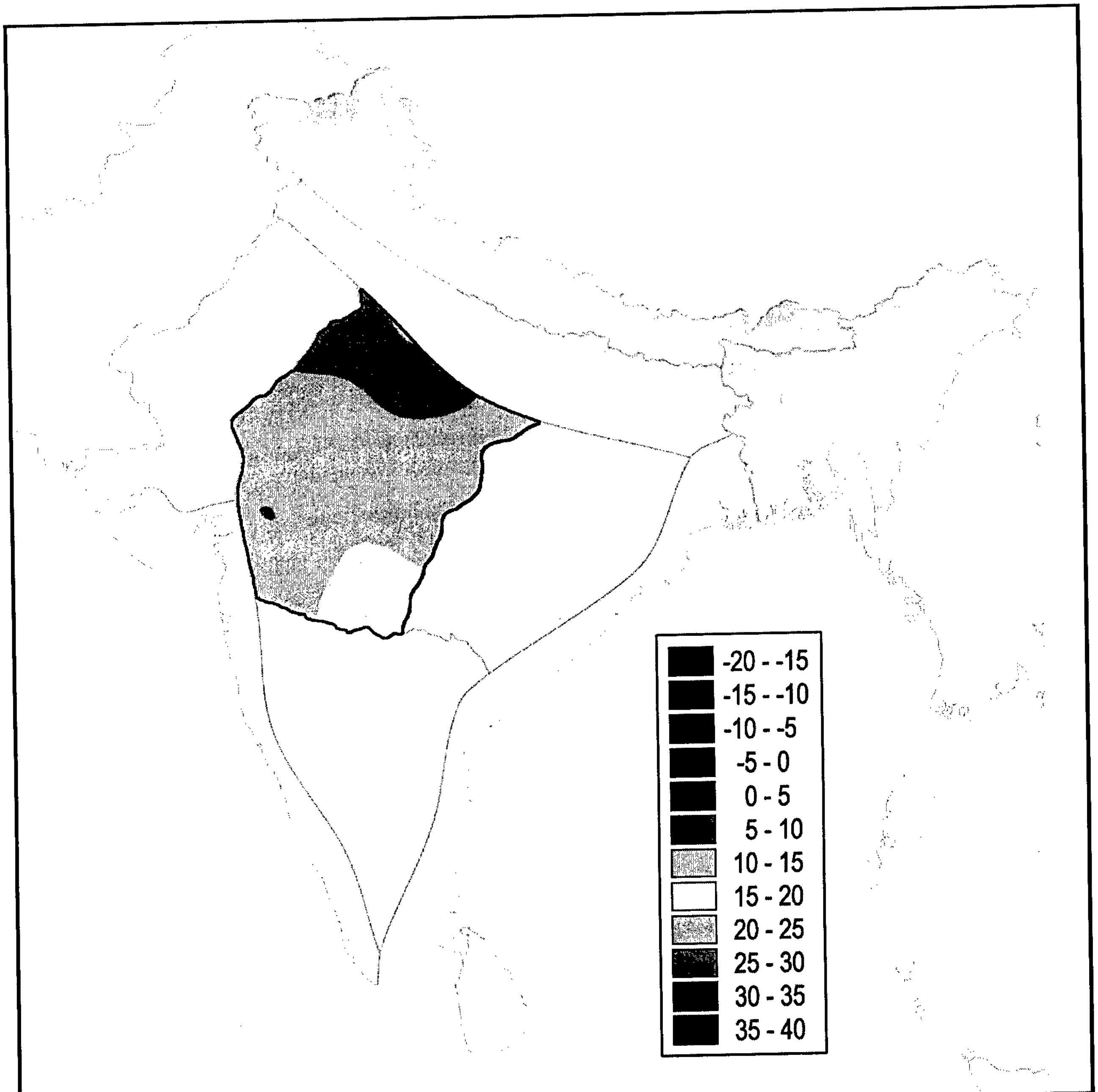


Figure 6-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for January. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other winter months may be higher, especially at the beginning and ending of the season.

General Weather. March through May is the driest as well as the hottest time of year. The equatorial trough (ET) is far south, and the subtropical jet is over or north of the Himalayas. Winds are light, and driven by differential heating rather than large scale, synoptic features. The transition to the southwest monsoon begins in May. The Asiatic high is significantly weaker and soon disappears. The Southern Hemisphere belt of high pressure builds, and the ET begins to move north. Often by late May, it is over southern India. Heat lows begin to develop over land in March. The Arabian Sea and Bay of Bengal are under the influence of slightly higher pressure than the Indian subcontinent. This occurs as the subcontinent heats up more quickly than the surrounding water which creates relatively higher pressure over the cooler ocean waters. This development assists in the production of thermal lows. By April, the thermal low has deepen significantly and has set up over India near 23° N. Flow begins to circulate around the lower pressure field, which creates some characteristics of a little monsoon or a "monsoon burst." Peninsular India south of 20° N begins to be influenced by maritime air masses. This maritime climate makes the heating over land more marked to the north of 20° N. Weak lows begin to develop over Sind, Bihar, and the eastern reaches of Uttar Pradesh, while a north-south oriented trough of low pressure forms through the center of India. By May, continental low pressure dominates the region. Its main core is over Sind and West Rajasthan, and extends as a trough through Orissa. The thermal low will continue to deepen through the hot season. When the circulation around the low begins to be fed by the trade winds deflected from the southern hemisphere, the monsoon invades the peninsular eastern coast. Over the lower Indo-Gangetic plain, where the difference in humidity is stronger, "Nor'westers"develop. Nor'westers, which typically move from the northwest to the southeast, are most frequent during the hot season, and end with the arrival of the southwest monsoon.

The primary air mass is continental tropical. The warm, dry air mass gets progressively heated during its passage across the arid regions of Iran, Baluchistan and Sind. In circulating around the heat low over northern India, it undergoes turbulent mixing and become increasingly unstable. Despite this unstable structure, the lack of moisture in the atmosphere restrains the development of clouds and precipitation. The continued intensification of the heat low over northwest India gives rise to strong dust storms that sometimes persist for several days. Very hot days with comparatively cooler nights and a large diurnal temperature range, clear to partly cloudy skies, gusty surface winds from noon till evening, dusty atmosphere in the afternoon and local haze in the morning, characterize the typical weather.

Typhoons, although uncommon, may occur in April and May. Typhoons bring torrential rain, and strong winds to the plains. Floods associated with typhoons can create devastation across the central region.

Sky Cover. Cloudiness increases in amount and in low cloud in proportion to total cloudiness as the season progresses. Cumulus clouds frequently develop during the afternoon, but rapidly dissipate at sundown. When sufficient moisture is present, cumulonimbus may develop over the Vindhya and Satpura Ranges. The average height of ceilings during the hot weather season is 4,000-5,000 feet. The occurrence of any ceiling is less than 20 percent of the time. Ceilings less than 3,000 feet occur less than 5 percent of the time in any month (see Figure 6-11). The highest percentage of 3,000 feet ceilings occurs around 1200Z (1700L), 4-7 percent of the time. Ceilings less than 1,000 feet rarely occur.

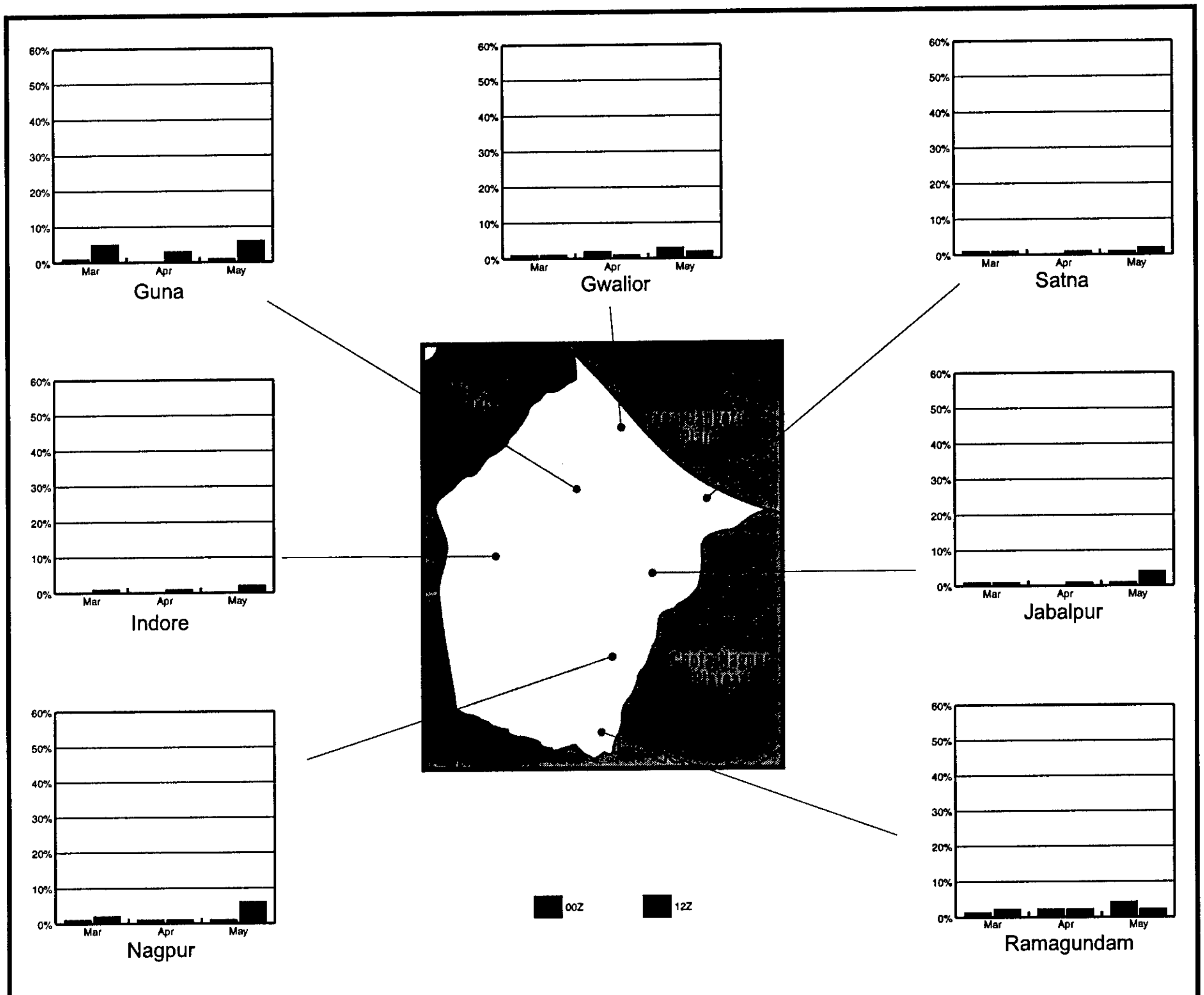


Figure 6-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percentage of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. The occurrence of fog and precipitation in most areas increases slightly from March to May. Overall visibility in the region averages 4-6 miles (6,000-9,000 meters). The worst visibility occurs around sunrise and the best in the afternoon and evening. As noted in Figure 6-12, visibility differs from one area to another, mainly due to the location of the stations relative to water sources. The principal restrictions to visibility are fog, dust, smoke, and haze. Topographic features and local conditions are key in the determination of visibility. In industrial areas, reduction in visibility may be experienced in association with smoke, which is worst at night and early mornings. Fog occurs less frequently as the season progresses.

Visibility less than 3 miles (4,800 meters) occurs less than 15 percent of the time. These lower visibility reports generally occur during the early morning. By afternoon, it drops to less than 5 percent of the time. Visibility less than 1 mile (1,600 meters) is rare.

Dust and sand storms are rare except in the northern regions adjacent to the Thar Desert. During a dry thunderstorm dust squall in the Thar Desert, dust is often lifted hundreds of feet and transported over the Central Highlands. Dust storms are most common in the afternoons, but may occur at any time. Dust raised by high winds often remains suspended in the air for a long time. Under intense dust storm conditions, dust will reduce visibility to less than 300 feet (less than 100 meters) for many hours. Dust storms are primarily associated with instability in the atmosphere in which winds often exceed gale force. An impending dust storm is usually preceded by a change in wind direction, a marked fall in temperature at the surface, and a rise in relative humidity. Thunderstorms are generally associated with these squalls but lightning may not be visible through the thick dust or thunder heard over the noise of the wind. Dust storms occur one day a month in the hot season throughout the south. In regions adjacent to the Thar Desert, dust storms occur more than 10 days a month.

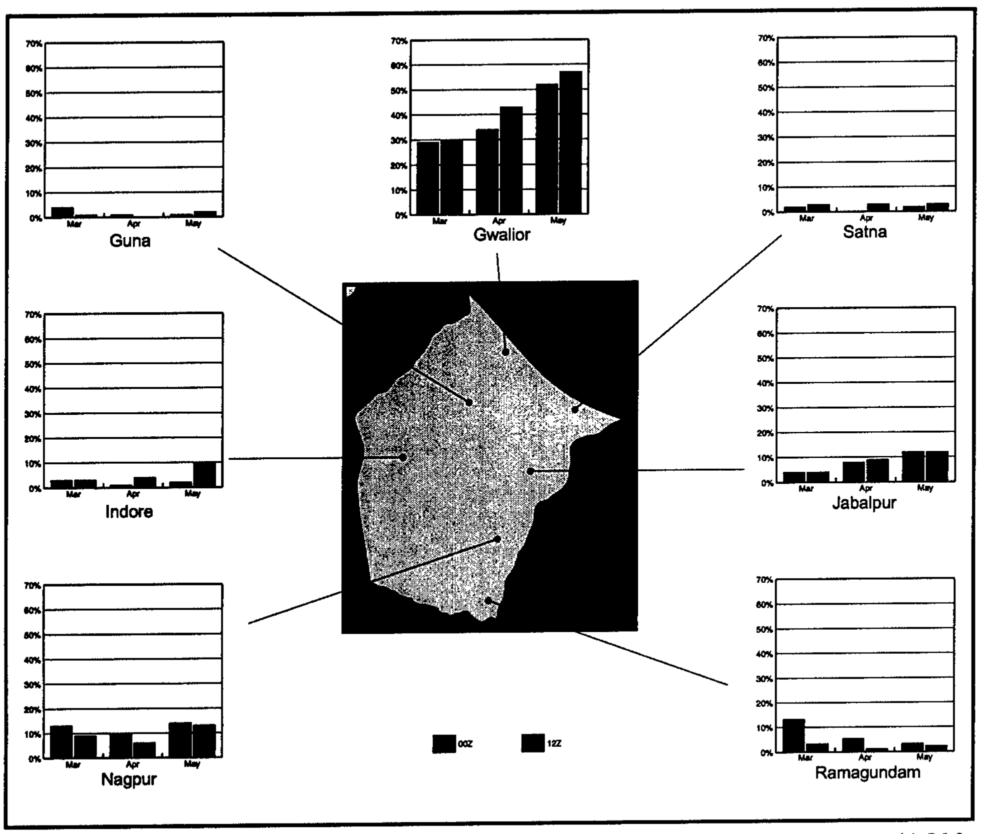


Figure 6-12. Hot Season Percent Frequency of Visibility below 3 Miles (4,800 Meters) for March to May. The graphs show a monthly breakdown of the percent of visibility below 4,800 meters based on location and diurnal influences.

Surface Winds. The winds begin the transition from northerly to a more westerly flow as seen in Figure 6-13. The southwest monsoon flow begins to become evident in the south by the end of May. The heat low has begun to set up to the northwest, and a surface "heat" trough develops through central India. To the west of this trough, winds are primarily northwesterly to westerly, while on the east side, winds become southerly to southwesterly. Surface winds are also altered by the diverse terrain, which is evident around all three mountain ranges of the region. Early in the season in evening through morning hours, conditions are primarily calm. When not calm, evening and early morning winds are generally light and variable. The winds become westerly through northwesterly at 5-7 knots by afternoon. Through the afternoon, surface winds are northwesterly 5-7 knots with infrequent southwesterly winds at 10-15 knots. By May, the winds are from the west or northwest at 5-7 knots at all hours. In the south central area, the winds become stronger in May with average afternoon speeds of 10-15 knots. This area experiences gusts in excess of 20 knots 10 to 15 percent of the time.

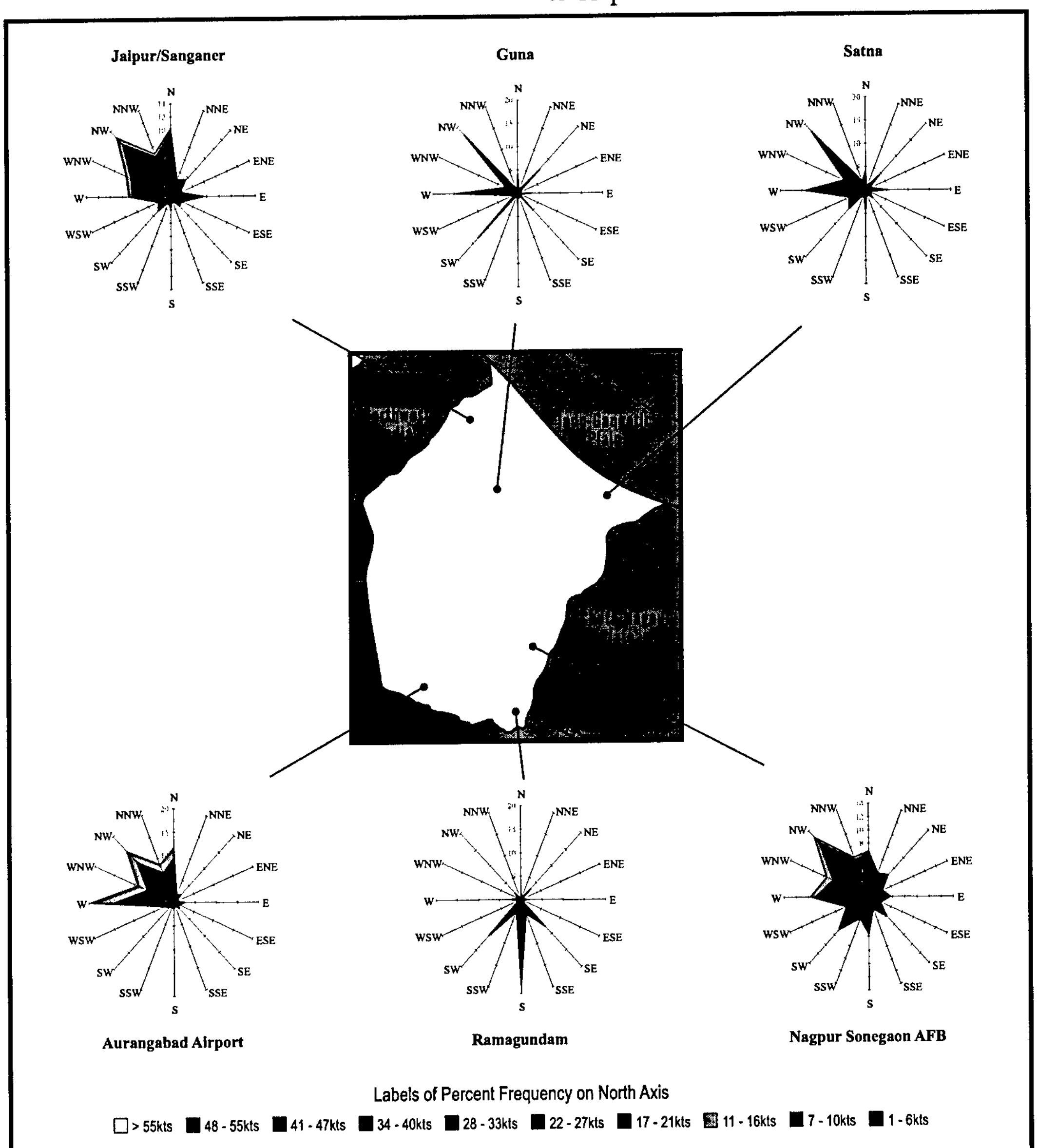


Figure 6-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The region remains under westerly winds throughout the hot season. Wind directions vary with latitude as well as height. Westerly flow prevails above 10,000 feet. Below 10,000 feet, winds are light and mostly from the west-northwest. At 700 mb, winds are westerly at speeds near 15 knots. The 300 mb winds are 30-60 knots; 90 knots will occasionally occur. The subtropical jet begins to move north near the end of the season, but the southern periphery of the jet brings west winds at speeds of up to 100 knots over northern India. Figure 6-14 shows the upper-air winds typically found at Aurangabad and Bhopal in April.

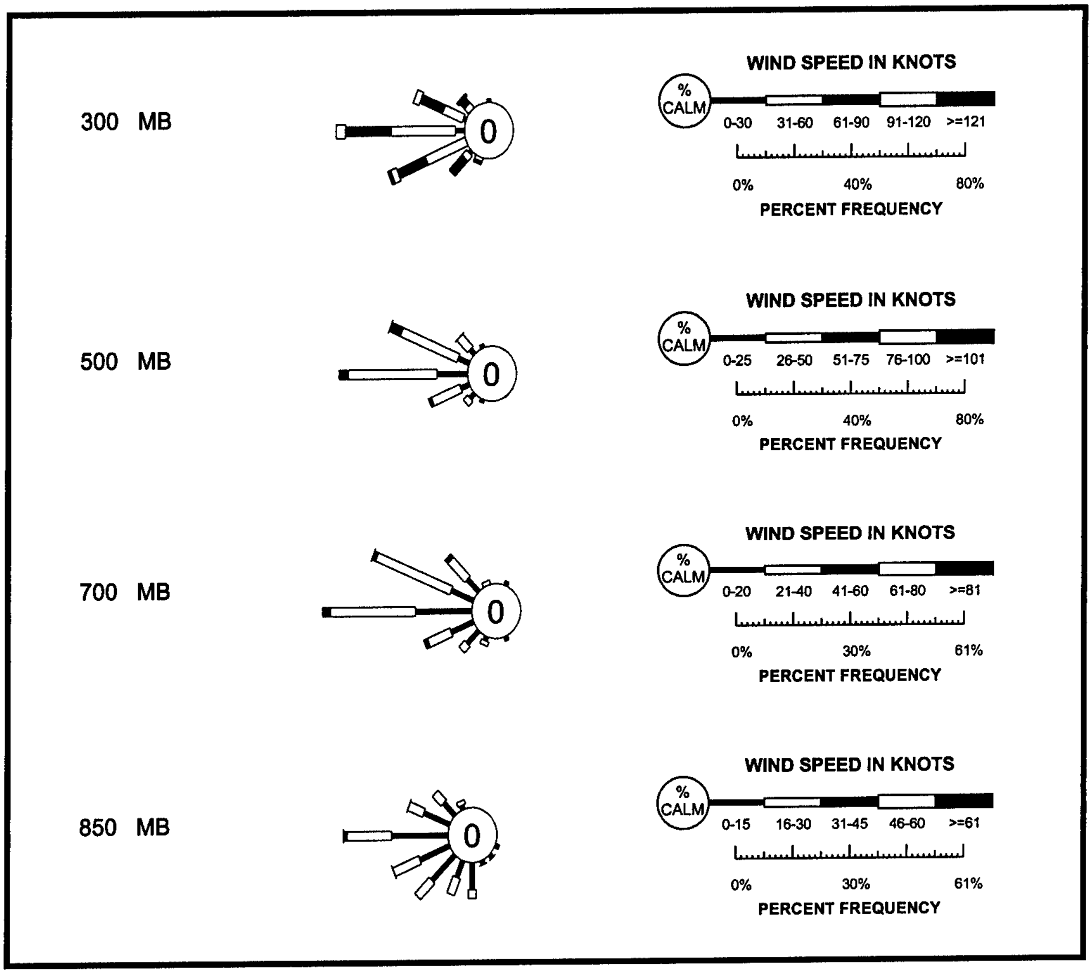


Figure 6-14. April Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Aurangabad and Bhopal.

Precipitation. There is little precipitation in this season. Terrain determines the distribution of precipitation over the region. The Western Ghats create a rain shadow just east of them, but the Satpura, Vindhya, and Aravalli Ranges are not significant barriers. The average rainfall throughout the region is less than 1 inch (25 mm). At the eastern base of the Western Ghats, the average precipitation amounts are 0.2 inch (5 mm). The average amounts increase eastward with accumulations of 0.7 inch (18 mm) in the eastern-most reaches of the region. The average is 2-3 days with precipitation a month in March and April; the frequency increases in May to 3-4 days. Maximum 24-hour precipitation is 1-2 inches (25-51 mm), and on extremely rare occasions can be as much as 5 inches (127 mm). Thunderstorms gradually increase through the season. One to two storms occur at most stations during March and April, except Nagpur, where as many as 4 thunderstorms occur in both months. By May, the frequency of thunderstorms increases to 3-5 days as the southwest monsoon approaches. Most precipitation associated with these thunderstorms evaporates before reaching the ground. Hail storms occur approximately once every five years. Figures 6-15 and 6-16 show April mean precipitation amounts and seasonal precipitation and thunderstorm days, respectively.

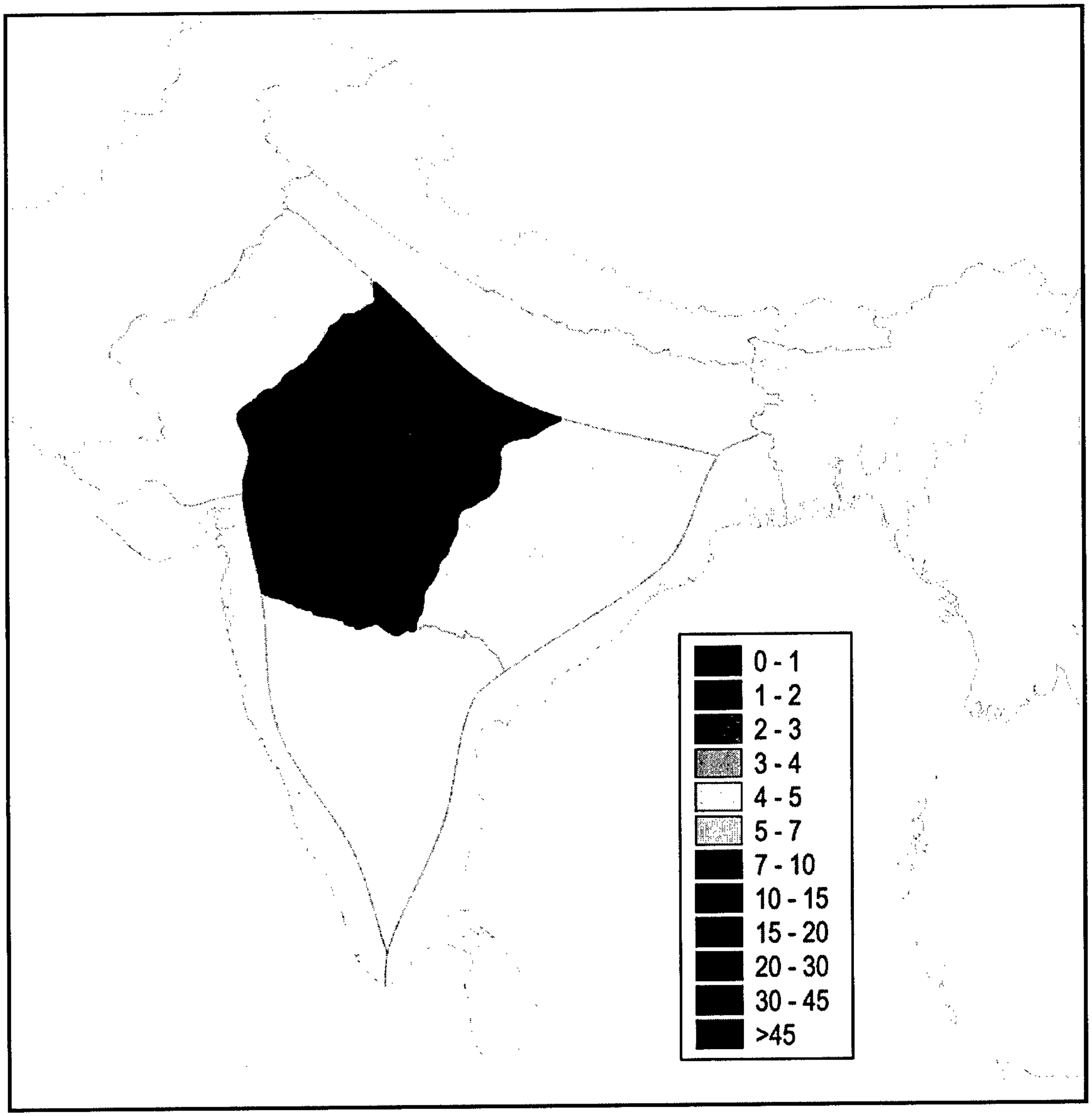


Figure 6-15. April Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

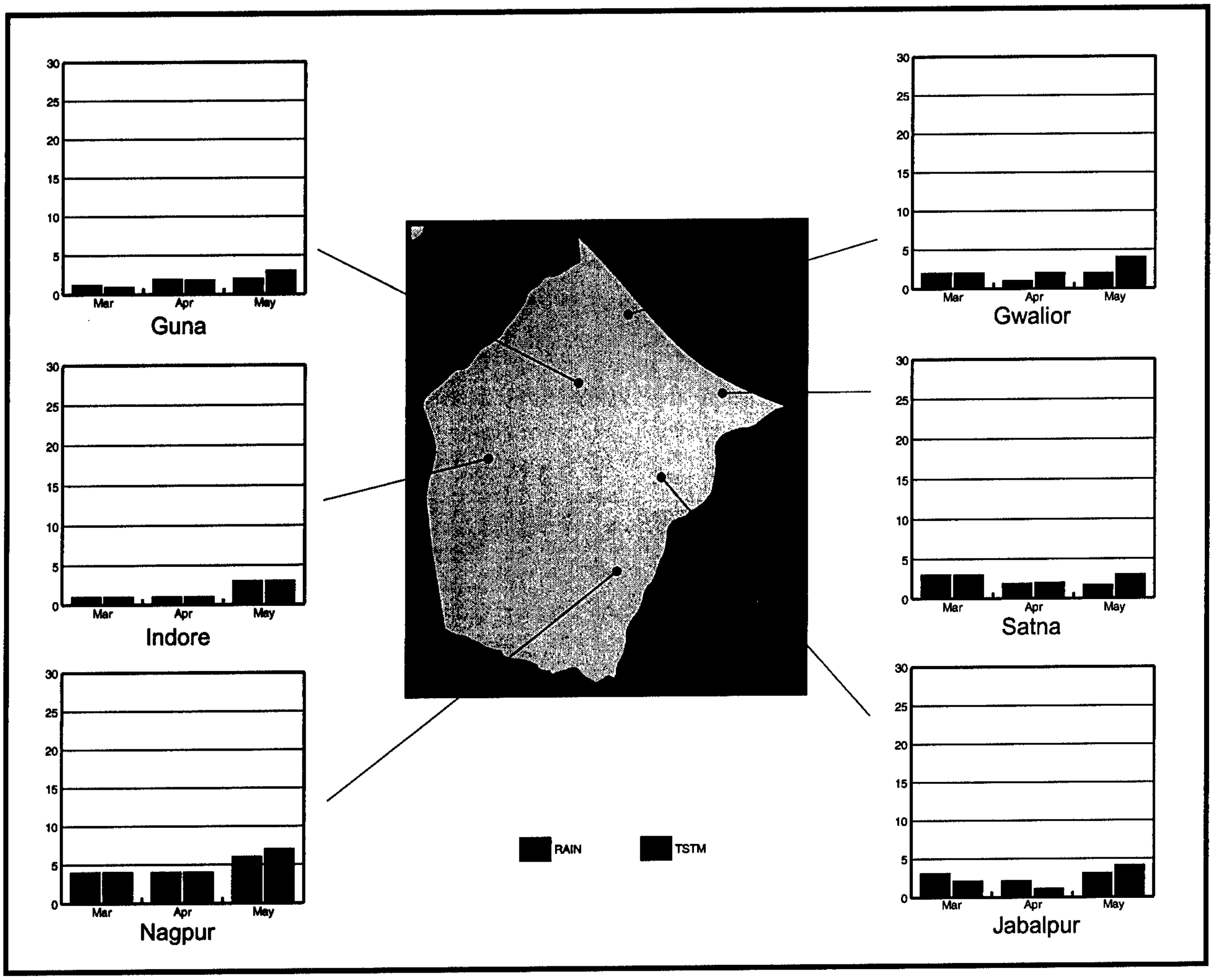


Figure 6-16. Hot Season Mean Precipitation and Thunderstorm Days, from March to May. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. The highest daily mean temperatures occur mostly in April and May. The mean highs range from 90° to 95°F (32° to 35°C) in March and increase to 100° to 105°F (38° to 41°C) in May. Kota, along the Chambal River, experiences the warmest mean high in the region of 115° F (46°C). The mean lows in March range from 56° to 59°F in the north (13° to 15°C), to the 69° to 72°F (21° to 22°C) in the south. These temperatures rise to 75° to 85°F (24° to 30° C) in May. The March extreme low recorded is 41°F (5°C) at Jabalpur, and the extreme high, recorded at multiple locations, is 120°F (49°C) in May. For most of the region, the mean diurnal temperature range is 30 Fahrenheit (14 Celsius) degrees. The average relative humidity during the afternoon is 20-25 percent. In the morning, the humidity averages 65-75 percent. Sudden rainfalls often provide short-term relief from the heat. Figures 6-17 and 6-18 show the April mean maximum and minimum temperatures, respectively.

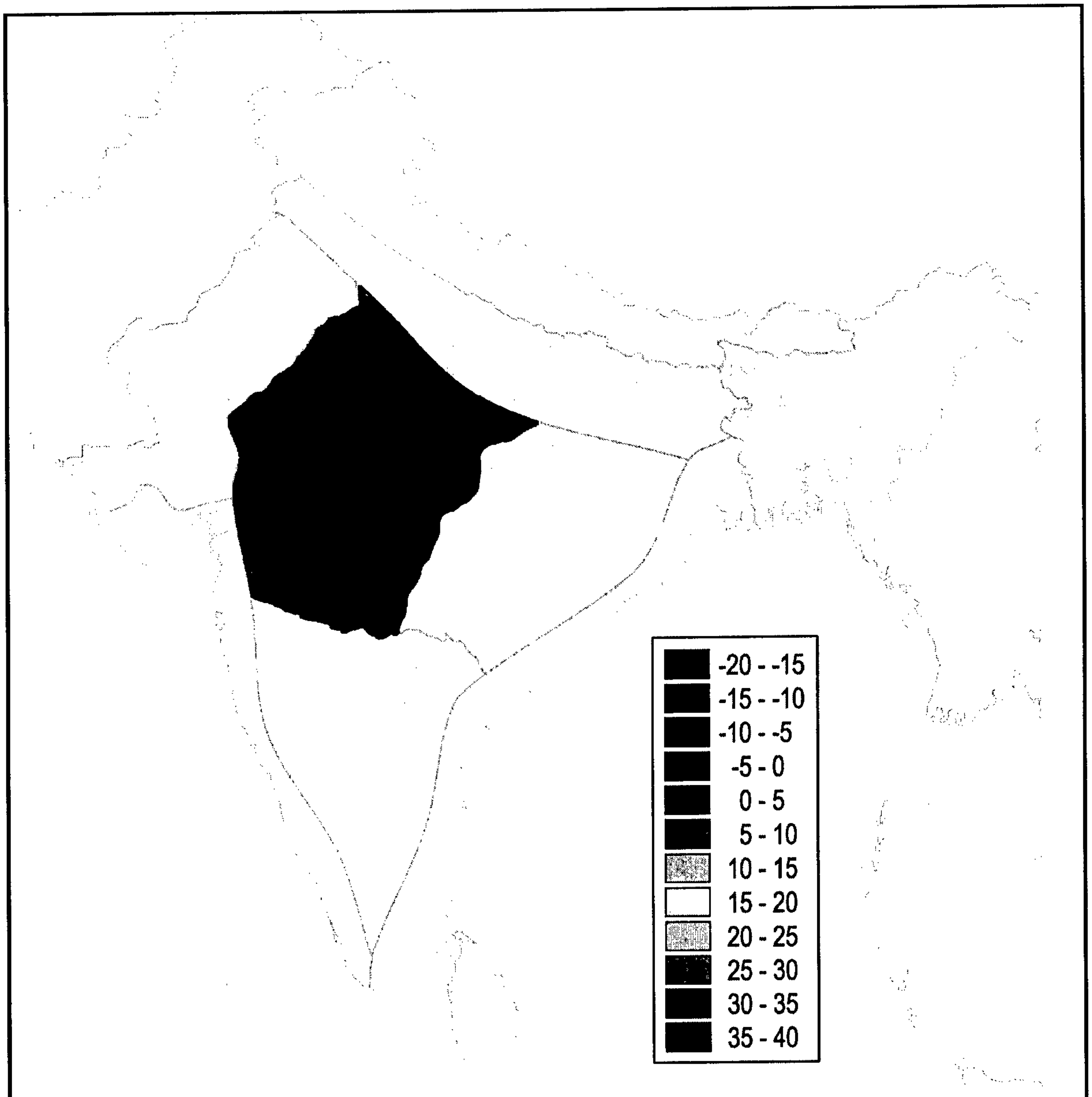


Figure 6-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

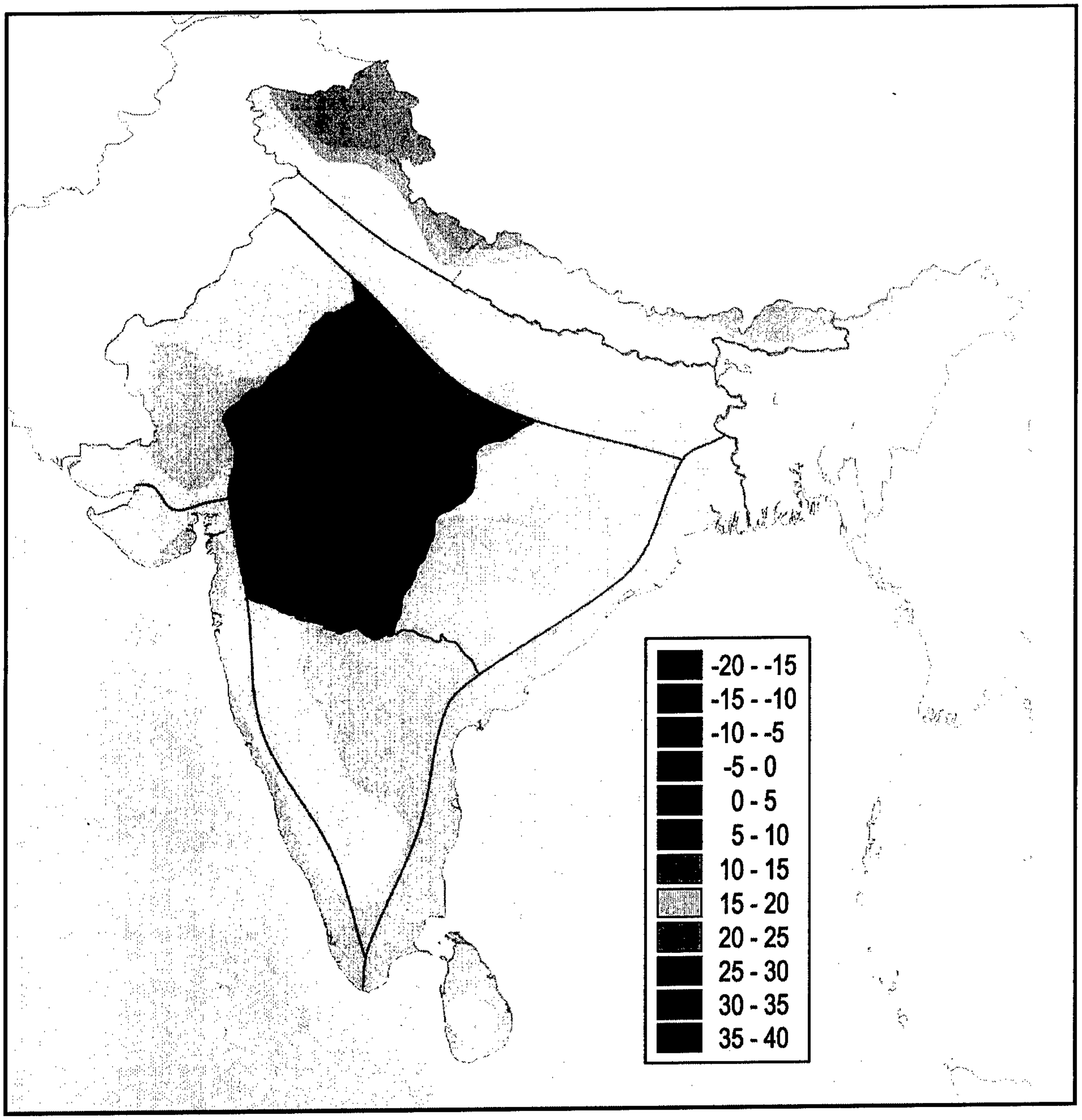


Figure 6-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. By the end of May, the monsoon trough lies over north India with the axis from Ganganagar to the northern part of the Bay of Bengal. The Indian Ocean high is strong and centered around 30° S and 60° E. The thermal high over Australia helps push the ET (monsoon trough) northward even as the Asiatic low pulls it. The ET moves to the northern Indian subcontinent by the end of June, and the whole area experiences southwest winds.

The development of the Somali jet brings a vast flow of warm, moist, unstable air into the northern Indian Ocean. The equatorial westerlies transport this air over South Asia to bring heavy, layered clouds, imbedded thunderstorms, and torrential rains. The southeast trades of the Southern Hemisphere cross the equator and become southwest winds as they are deflected in the Northern Hemisphere. During the southwest monsoon, the Somali jet funnels Southern Hemisphere moisture across the Arabian Sea into India, while the TEJ provides an outflow mechanism for disturbances of all types in both the Arabian Sea and the Bay of Bengal. This jet is strengthened by the India-Myanmar trough, which develops over the Bay of Bengal. The southwest monsoon has 2 branches: the Arabian Sea branch, which crosses the Western Ghats in peninsular India as a west-to-southwest winds, and the Bay of Bengal branch. The southwest monsoon current normally advances into Bangladesh and the tip of the peninsula by late May and moves north and west from there.

The two primary air masses that influence the region during the southwest monsoon are maritime tropical and the modified maritime tropical. The maritime tropical air mass usually exists south of 22° N, where the prevailing wind is southwest to west. This air mass is modified in the lower levels as it travels over the warmer surface and in the upper levels by mixing with the warm easterlies. Weather features are associated with moderate day temperatures and low diurnal ranges, cloudy to overcast skies, mainly stratus, stratocumulus, altostratus and nimbostratus with bases at 2,000 feet or lower, with frequent rain or drizzle in and around mountains. Once the air mass becomes modified maritime tropical, the days and nights become slightly warmer. Cumuliform clouds become more common as do showers and thunderstorms. Cloud bases are usually higher, an average of 3,000 feet. Surface winds remain generally light to moderate except in periods of showers where they become stronger and gusty.

Monsoon depressions that develop in the northern Bay of Bengal and track across the peninsula bring copious rain to India. When the tropical easterlies override the southwest monsoon flow, the easterly waves that develop in this strong air current help form monsoon depressions and tropical storms in the Bay of Bengal. Mid-tropospheric cyclones in the north Arabian Sea bring additional torrential rains to the west coast, and a rain-shadow effect east of the Western Ghats.

A weak ridge forms in the Arabian Sea off the southwest coast. This turns the air stream to the northwest. Precipitation increases on northwest slopes in the western areas of the region. In September, the southwest monsoon begins its retreat. The Pakistani heat low begins to weaken and fill, and the Asiatic high builds. By mid- to late September, the ET usually crosses south of the northern areas. The ET makes a fairly steady retreat; this is contrary to its erratic north and south oscillations while on its northward advance. As the ET passes, heavy rains and thunderstorms accompany it. Behind the ET, the northeast flow begins to reestablish itself.

Sky Cover. Mean cloudiness increases dramatically with the onset of the southwest monsoon. During this season, clouds are mainly stratiform in the low and middle levels. The lee side of the Western Ghats experience less clouds. Frequent cumulus and occasional cumulonimbus clouds form along the Vindhya and Satpura Ranges. Low stratus around these hills is not uncommon in mornings after evening rains. In the latter half of the summer season, there is more cloudiness in the afternoons than in the mornings. It is cloudy as much as 70-90 percent of the time during the monsoon season. In the afternoon, ceilings less than 3,000 feet occur up to 60 percent of the time in the south, and less than 30 percent in the north and in the lee of the Western Ghats. Through the night, the frequency of low ceilings decreases 10-20 percent of the time. Figure 6-19 shows the seasonal percent frequency of ceilings below 3,000 feet for the Cenral Highlands. Ceilings below 1,000 feet occur less than 10 percent of the time throughout the entire region. During thunderstorms and heavy downpours the ceiling will briefly lower to less than 1,000 feet. July and August are the most cloudy months, and September is the least. The southwest monsoon begins to retreat in September so cloudiness decreases rapidly.

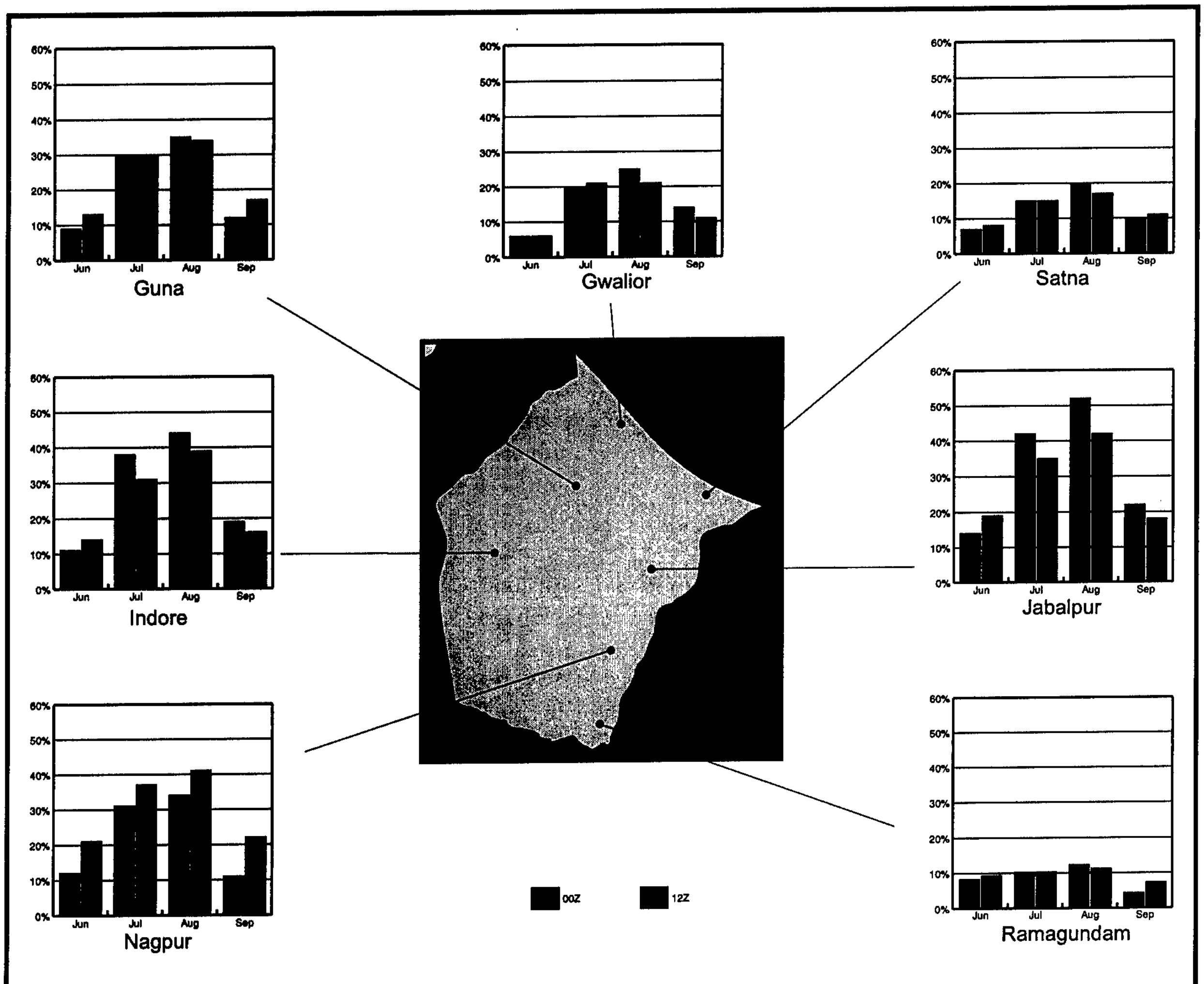


Figure 6-19. Southwest Monsoon Percent Frequency of Ceilings below 3,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. The frequency of lower visibility increases from June through August, then decreases significantly in September. The principal restrictions to visibility are fog, rain, dust, smoke, and haze. At the height of the southwest monsoon season, afternoon visibility less than 3 miles (4,800 meters) occurs 25-35 percent of the time; in the evening, the frequency decreases to 10-15 percent of the time. By September, occurrences visibility below 4,800 meters decrease to 10-20 percent of the time in the night and 5-10 percent of the time in the afternoon. Overall, the worst visibility occurs around sunrise and the best in the afternoon and evening. As noted in Figure 6-20, visibility differs from one area to another, mainly due to site positions relative to water sources. Terrain and local conditions are of paramount importance in the determination of visibility. In industrial areas, reduction to visibility occurs with smoke that is worst at night and early mornings. Visibility less than 1 mile (1,600 meters) is rare.

Dust and sandstorms are infrequent during the southwest monsoon except in areas adjacent to the Thar Desert. During a dry thunderstorm dust squall in the Thar Desert, dust is often carried into the Central Highlands. Dust storms are most common in the afternoons but may occur at any time. Under intense dust storm conditions, visibility remains less than 300 feet (less than 100 meters) for many hours. Dust storms are primarily associated with winds that often exceed gale force. An impending dust storm is usually preceded by a change in wind direction, a marked fall in temperature at the surface, and a rise in relative humidity. Dust storms occur 1 day a month in the south and 4-5 days a month adjacent to the Thar Desert.

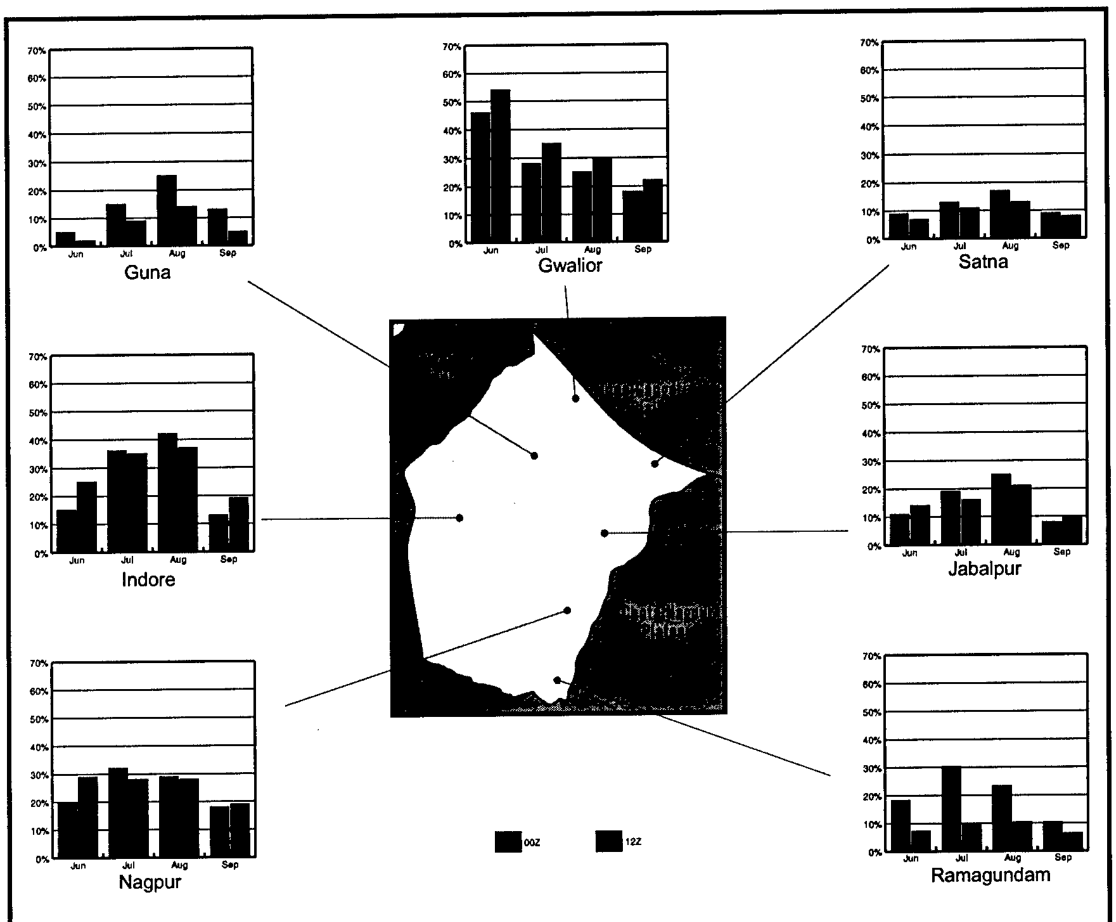


Figure 6-20. Southwest Monsoon Percent Frequency of Visibility below 3 Miles (4,800 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,800 meters based on location and diurnal influences.

Surface Winds. The predominant wind flow through most of the region is westerly as seen in Figure 6-21. These westerly winds are rather strong with an average speed of 10-15 knots, and occasionally greater than 25 knots. Winds hold more of a southwesterly component in the southwest. These winds generally last from June through August before they take on a westerly component, average speeds 5-10 knots. In mid-September, the winds begin to decrease in speed and become variable as the pressure gradient weakens. Upslope and downslope winds associated with diurnal heating occur in and around the Western Ghats. With strong pressure gradient, channeling may cause strong winds through valleys and mountain passes. The diverse terrain throughout the entire region also alters surface winds, which is evident around all three mountain ranges within the region.

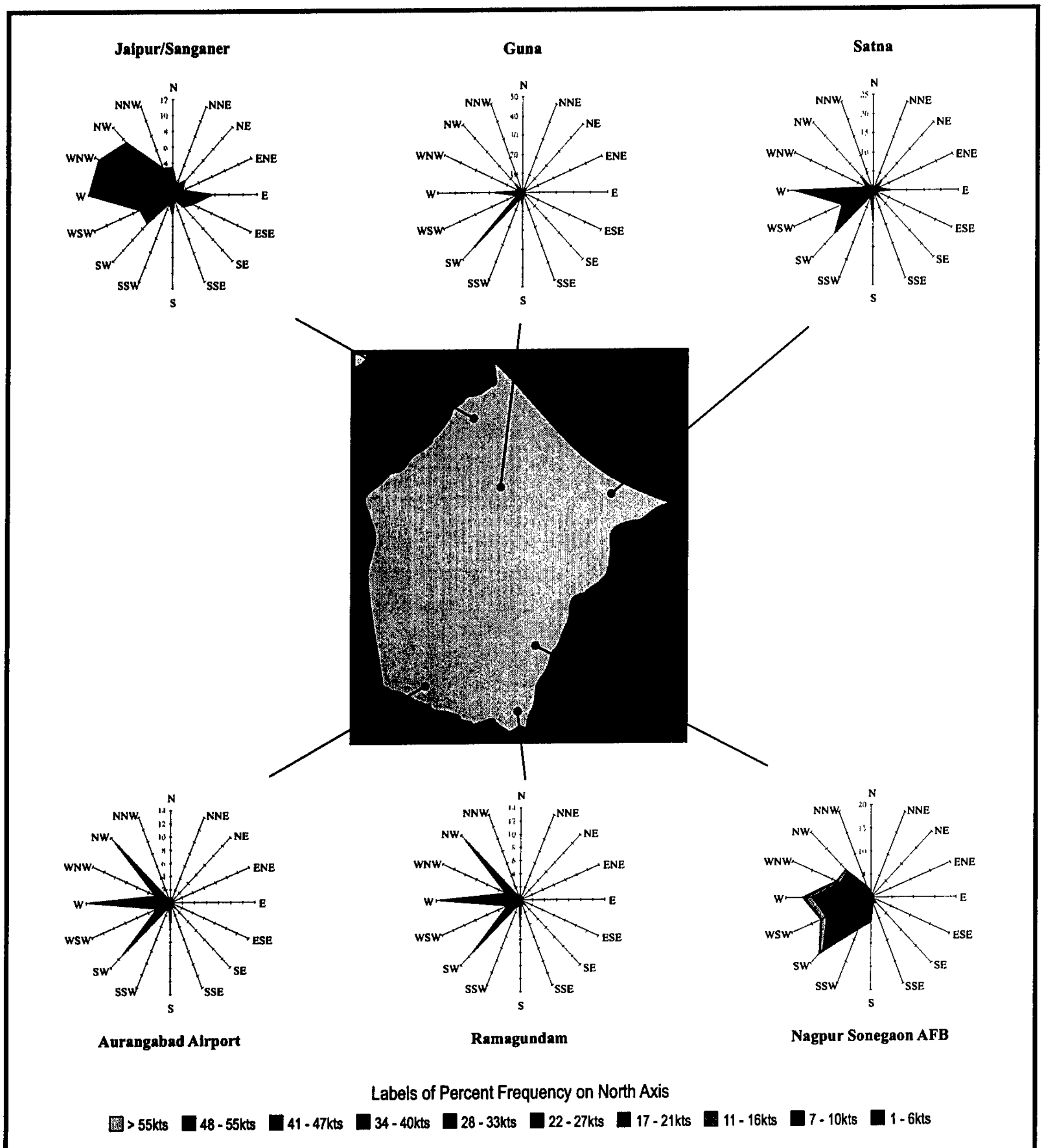


Figure 6-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Three upper-air wind patterns exist in South Asia: the monsoon westerlies, the tropical easterlies, and the bands of alternating upper-level westerlies and easterlies. The monsoon westerlies reach 700 mb. Winds in the monsoon westerlies are generally 25-50 knots. Tropical easterlies prevail to 300 mb with speeds generally near 30 knots, but reach 60 knots at higher levels. The oscillating bands of alternating westerlies and easterlies in the upper atmosphere rise and fall in a subsidence/convective cycle that shifts the bands from the top to the bottom over a 2-year period. Figure 6-22 shows the upper-air winds typically found at Aurangabad and Bhopal in July.

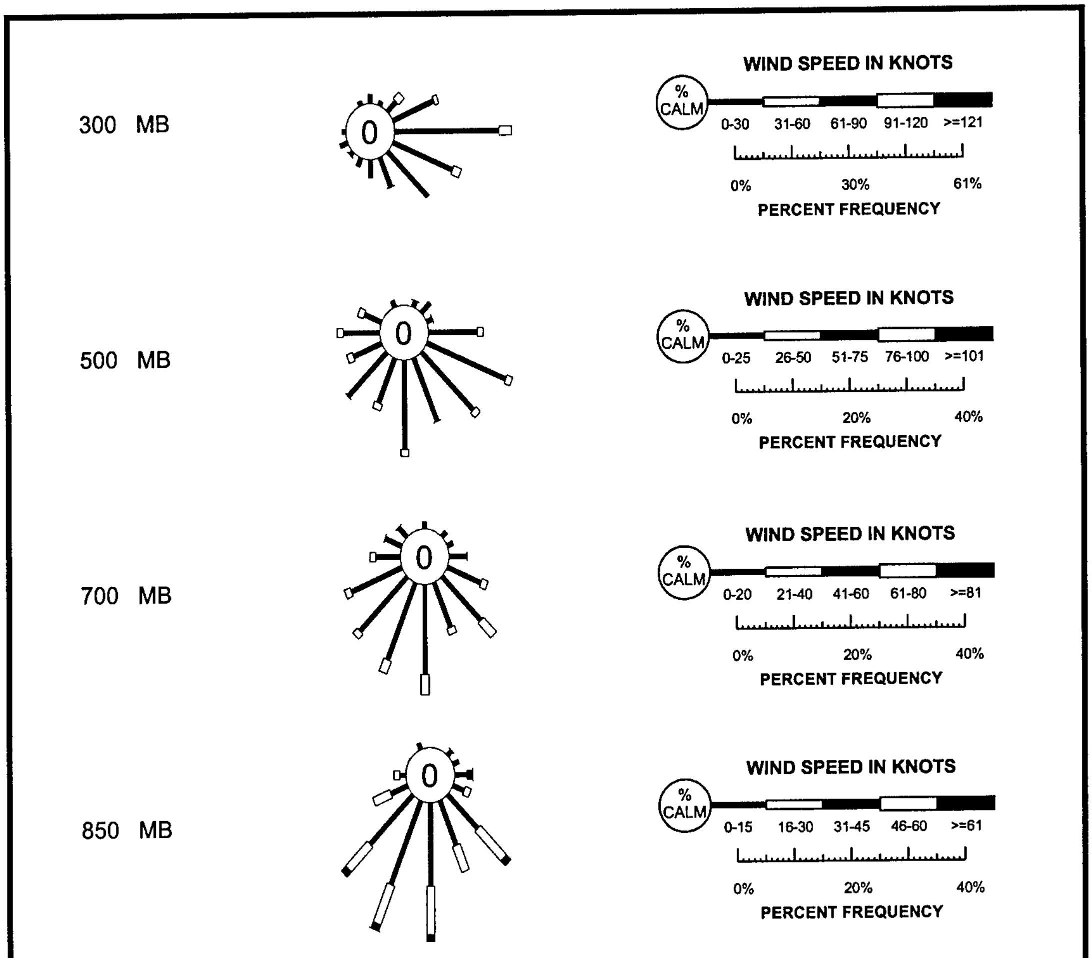


Figure 6-22. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Aurangabad and Bhopal.

Precipitation. A downpour, often with strong thunderstorms, generally initiates the rainy season. The monsoon has a pulsating character as bursts of rain alternate with partial breaks. There is an enormous variation between one area and another, primarily caused by the orientation and strength of the monsoonal flow and the topography. Normal rainfall accumulations change radically if the monsoonal flow significantly deviates from its usual orientation.

Southwest monsoon rains generally do not significantly affect the area until mid-June. Average precipitation for June is 6 inches (152 mm) over 6-11 rain days. In July and August, rainfall more than doubles at most locations to an average of 15-20 inches (381-508 mm) over 16-24 days. Exceptions to this include the northwest corner and the lee of the Western Ghats. In the northwestern corner of the region, which includes Jaipur, 5-7 inches (127-178 mm) of rain occur, and 7-15 days with rain occur. The primary reasons for this are drier air off the Thar Desert and a slight rainshadow associated with the Aravalli Hills. Lee of the Western Ghats, which includes Aurangabad, is another area where average rain and rain days are lower than the interior because of rain shadowing. The average amount of rain for July and August is 7-8 inches (177-203 mm). By September, precipitation amounts decrease to 5-10 inches (127-254 mm).

Thunderstorms gradually increase through July and August, then decrease slightly in September. As few as 3 thunderstorms per month occur in the lee of the Western Ghats, while the Nagpur area gets as many as 13 per month. The June average of thunderstorms in the rest of the region is 6-7. In July and August, the rate increases to 8-10 a month. By September, the frequency drops to 4-6 days. Hail rarely occurs. Figures 6-23 and 6-24 show the mean precipitation amounts for July and seasonal precipitation and thunderstorm days, respectively.

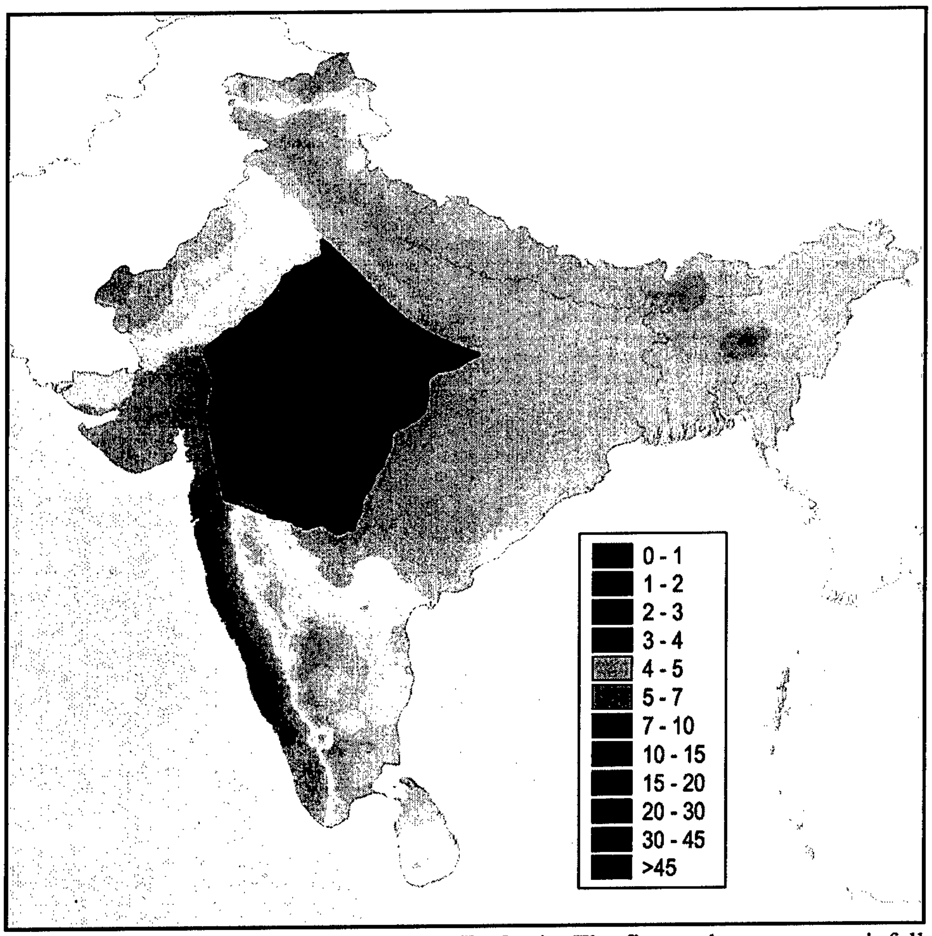


Figure 6-23. July Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

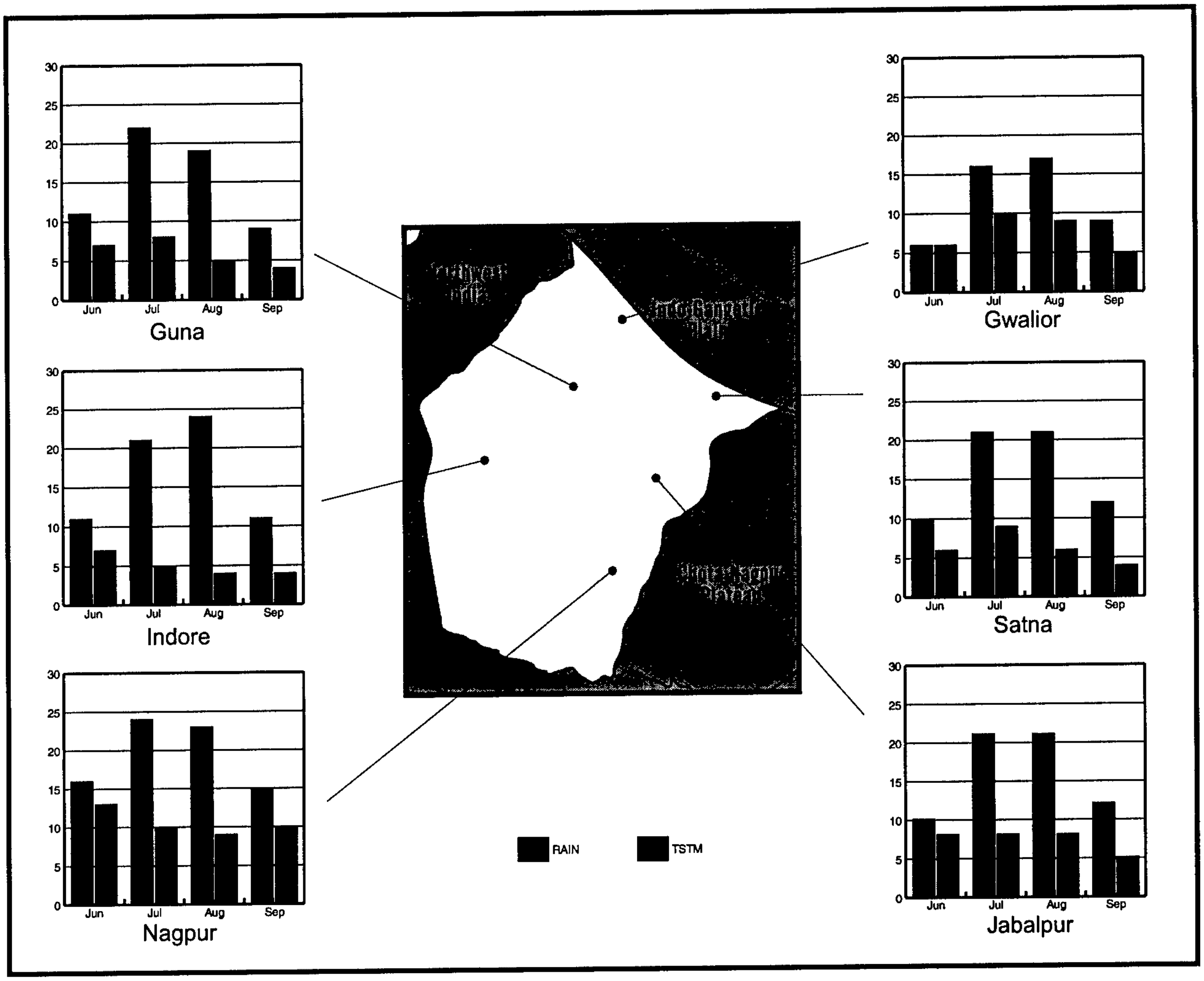


Figure 6-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Temperatures during the southwest monsoon decrease slightly with the increase in cloud cover, but relative humidity increases. The mean lows range from 73° to 79°F (23° to 27°C), and the mean highs are 84° to 102°F (29° to 39°C). The extreme low temperature is 50°F (10°C) in July at Aurangabad, and the extreme high is 120°F (49°C) in June at Gwalior. The area's highest temperatures occur in the northwest region adjacent to the Thar Desert, while lowest temperatures occur in the higher elevations alee of the Western Ghats. For most of the region, the mean diurnal temperature range is 15 to 20 Fahrenheit (8 to 11 Celsius) degrees. The average relative humidity during the afternoon is 70 to 75 percent. In the morning, the humidity averages 75 to 80 percent.

The dynamics associated with an El Niño event frequently create a significantly weaker monsoon season. This, in turn, creates less precipitation and cloud cover, and an increase in solar radiation, which results in higher temperatures in the region. The reverse affect occurs with La Niña events. An increase in cloud cover and precipitation results in lower temperatures during the southwest monsoon. Figures 6-25 and 6-26, show the respective July mean maximum and minimum temperatures.

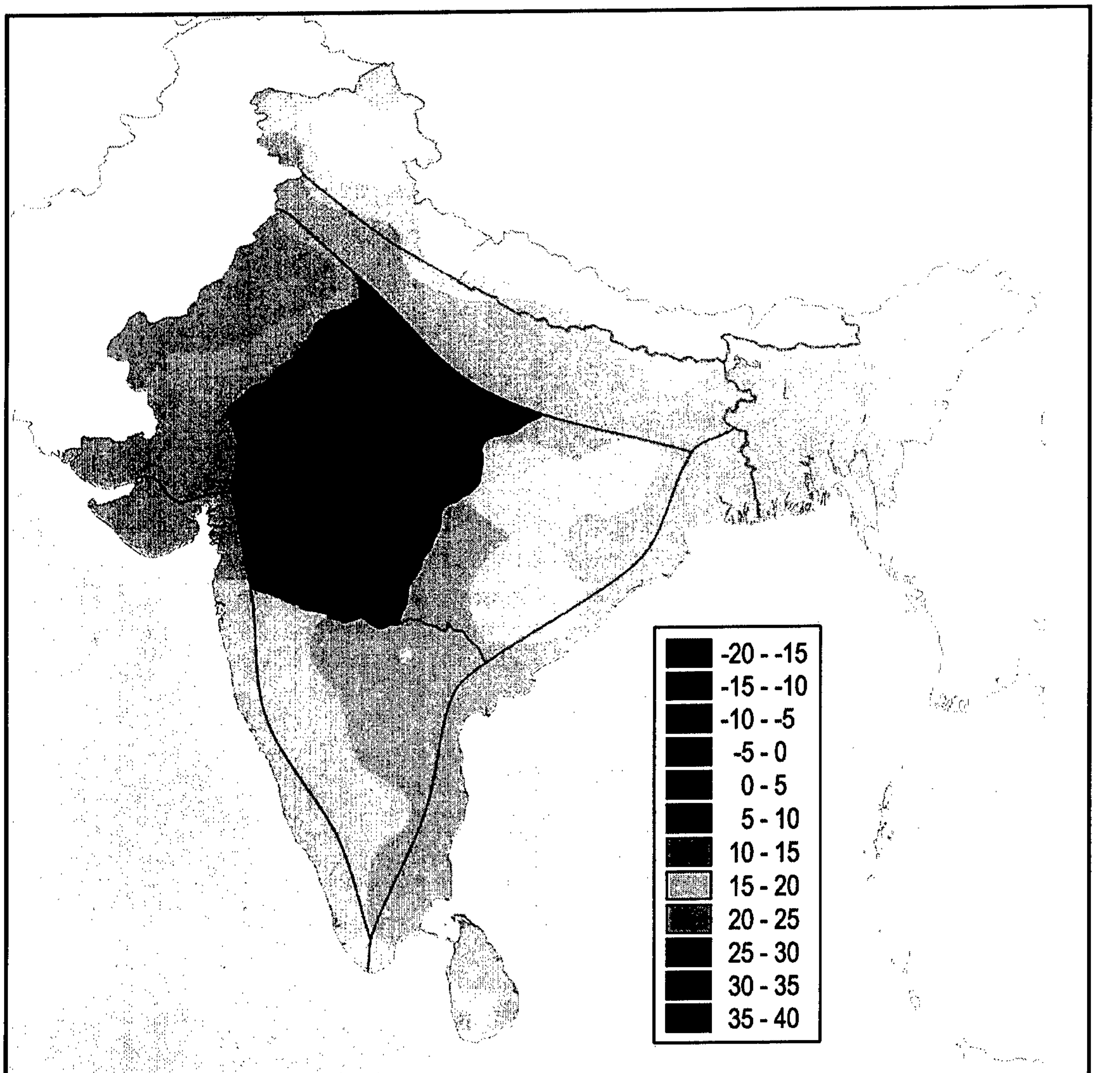


Figure 6-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other southwest monsoon months may be lower, especially at the beginning and ending of the season.

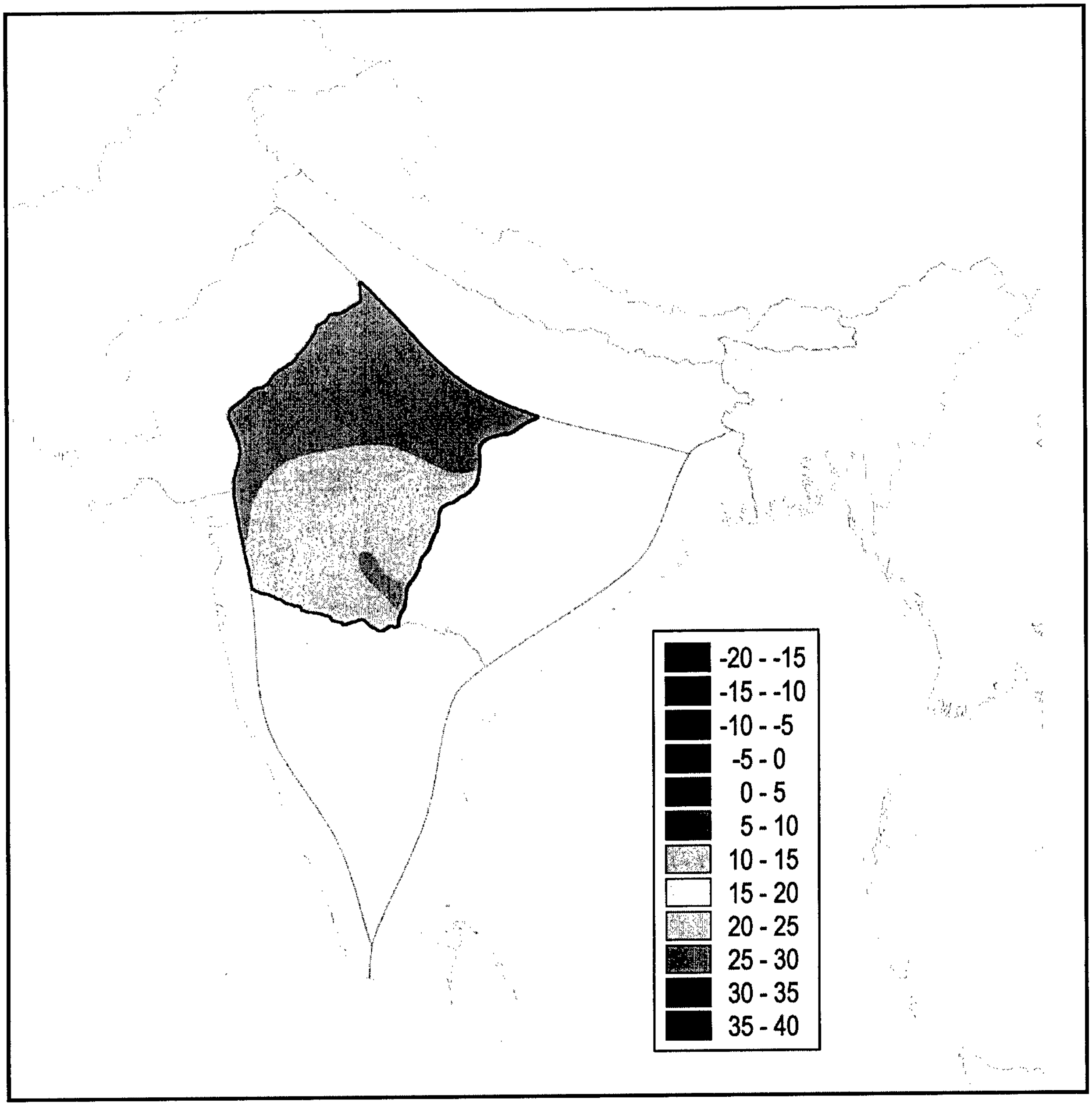


Figure 6-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other southwest monsoon months may be lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. Post-monsoon weather is partly cloudy, hot, and dry. By October, the Asiatic high is stronger, and the North Pacific high begins to move south. In response to these changes, the equatorial trough (ET) drifts towards the equator, but stays around 15°N in October. By late November or early December, the ET usually clears the southern tip of India. As it passes, it brings heavy rain and thunderstorms. Normally, the southwest monsoon retreats in a series of intermittent surges in the first part of September. The elements that drive the southwest monsoon, the equatorial westerlies, the Somali jet, the tropical easterly jet, and the India-Myanmar trough, all begin to disappear. The upper-level easterlies move well south, and the subtropical jet moves south of the Himalayas. This opens the path for early-season winter lows to move with the jet across northern India.

The air masses are partly continental tropical and partly modified continental polar. Occasionally in October and more frequently in November, the modified continental polar air reaches the northwestern portion of the area and sometimes farther south and east under the influence of western disturbances that travel across northern India. This air mass brings dry weather, high daytime temperatures, cool night temperatures, good to excellent visibility, and light to moderate surface winds.

Tropical disturbances develop along the line of discontinuity between the equatorial winds and the northeast trades; 46% of the cyclones develop in October and November and 62% in September through November. In general, these disturbances move towards the west, but on rare occasions, they penetrate the interior. Some of these storms become very violent and bring torrential rains and strong winds to the peninsula. By the end of November, the northeast flow is usually established.

Sky Cover. The abundant low and middle stratocumulus clouds of the southwest monsoon are replaced by the limited and more varied cloudiness of the northeast monsoon. The first sharp decline in cloud cover occurs in October in the north. Cumulus clouds develop in the afternoon and dissipate with the approach of evening. In the early mornings over the river valleys, low stratus may develop but rapidly dissipates shortly after sunrise. There are ceilings at any level less than 20 percent of the time. The average rate of ceilings less than 3,000 feet is under 5 percent of the time (see Figure 6-27). Aurangabad experiences a greater frequency than the rest of the region, with ceilings less than 3,000 feet 14 percent of the time at 0600Z. The primary reason for the greater frequency is upslope: East-southeasterly winds are pushed against an east-west branch of the Western Ghats. After 1200Z, winds become northeasterly and the frequency drops to 6-7 percent of the time. Ceilings less than 1,000 feet rarely occur. Most low ceilings occur between 0600Z and 1200Z.

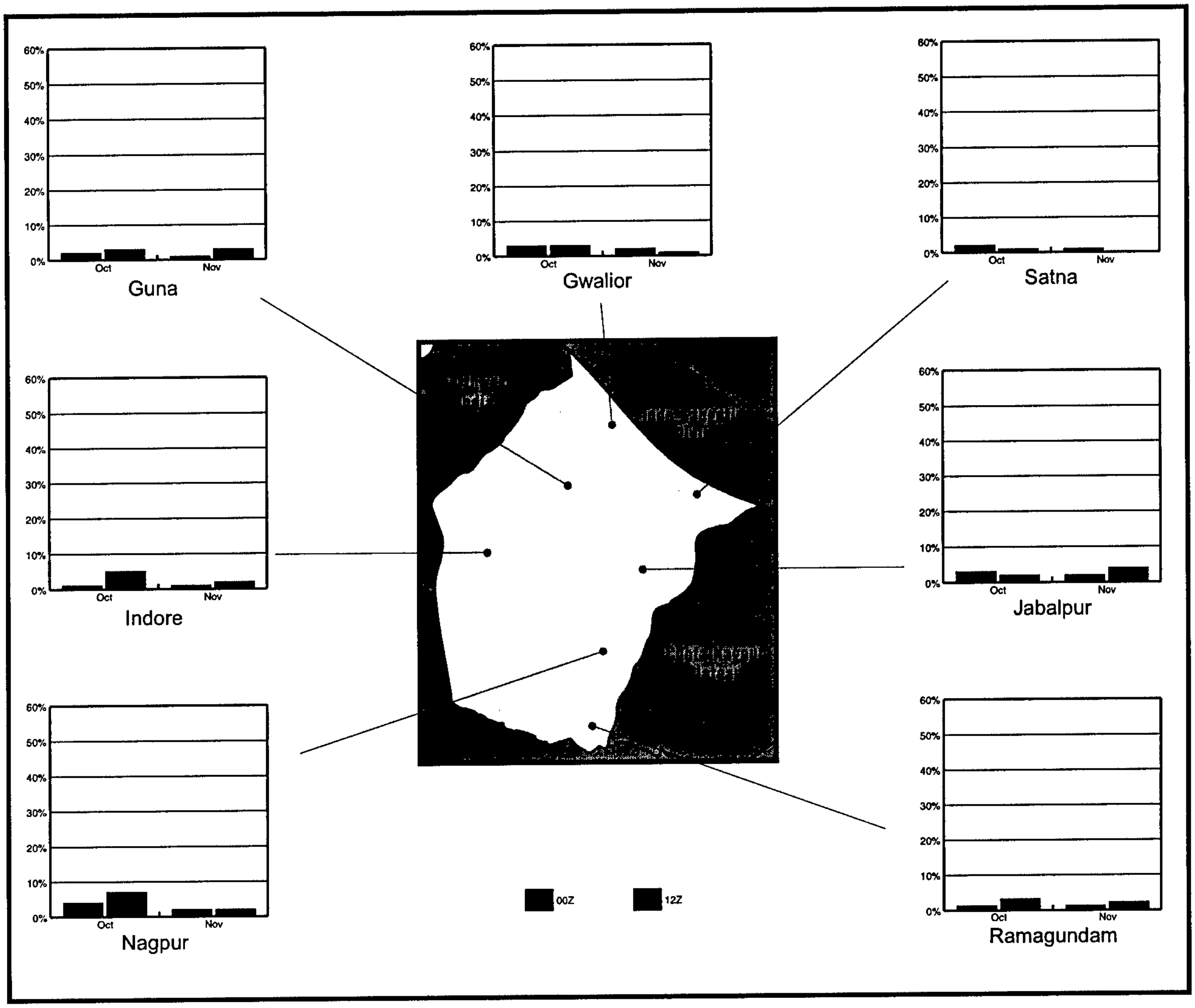


Figure 6-27. Post-Monsoon Percent Frequency of Ceilings below 3,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. Restricted visibility depends strongly on topographic features and local conditions. In industrial areas, reduction in visibility occurs with smoke, which is worst at night and early mornings. Smog is most common in the mornings in industrial cities. The principal restrictions to visibility are fog, dust, smoke, and haze. Fog occurs most often, largely due to nocturnal cooling, which creates radiation inversions. River valleys have a greater frequency of fog. In these areas it occurs mostly during the early morning hours. The height to which fog extends varies from shallow ground fog to about 1,000 feet in upslope fog along the Vindhya and Satpura Ranges. The highest frequency of fog occurs along the Vindhya Range, where it forms in the early morning hours and dissipates by midmorning. Average duration is 3-5 hours. Dust storms or sandstorms occur once a month in the northwest; elsewhere, they occur infrequently.

Visibility less than 3 miles (4,800 meters) occurs less than 10 percent of the time in much of the region (sse Figure 6-28). In and around major industrial centers, occurrences of visibility less than 4,800 meters increases to 15-20 percent of the time. Nagpur experiences visibility less than 4,800 meters as much as 23 percent of the time in October and 42 percent of the time in November. This drastic difference is primarily because Nagpur is an industrial city in a valley; the city's pollution becomes trapped below the low inversion and creates poor visibility for long periods of time. New Delhi, which is north of the region, produces a massive amount of pollution that flows down the river valley into the region southeast of the city. Gwalior, for instances, experiences visibility below 4,800 meters up to 40 percent of the time in October and 59 percent of the time in November. Visibility less than 1 mile (1,600 meters) is rare.

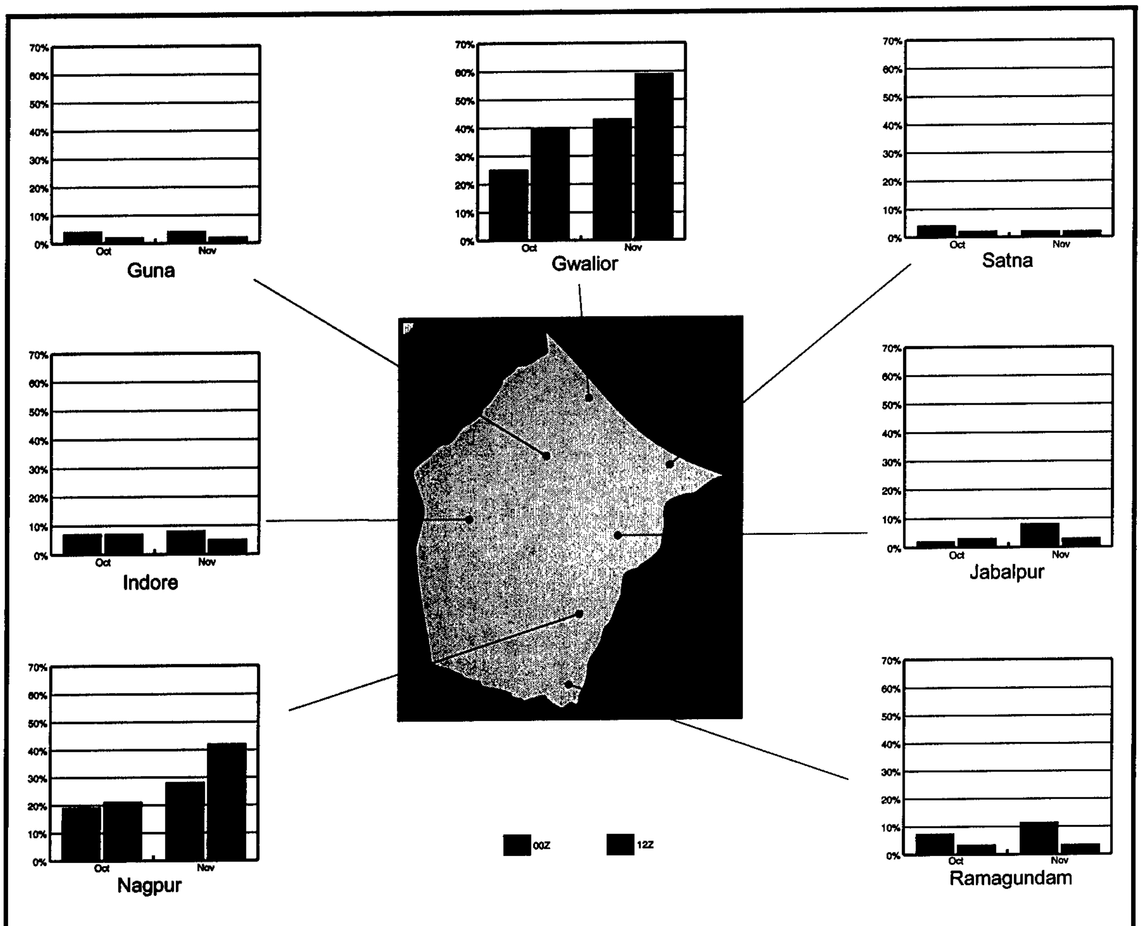


Figure 6-28. Post-Monsoon Percent Frequency of Visibility below 3 Miles (4,800 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,800 meters based on location and diurnal influences.

Surface Winds. The prevailing winds are north-northeasterly as seen in October wind roses for selected Central Highlands locations in Figure 6-29. During the fall, it is extremely rare for winds to exceed 25 knots. The widely varied terrain plays a significant role in wind direction. The winds are north or northeasterly at 5-7 knots during the afternoon. In the evening, conditions are calm more than 60 percent of the time at most locations. In the south, winds are slightly stronger. During the evening, winds are variable at 5-7 knots, and during the day, they are southeasterly at 10-15 knots. With the stronger winds, dust storms occur. Dust storms occur once a month on average in the northern areas of the region in strong winds. In the south, dust storms rarely occur.

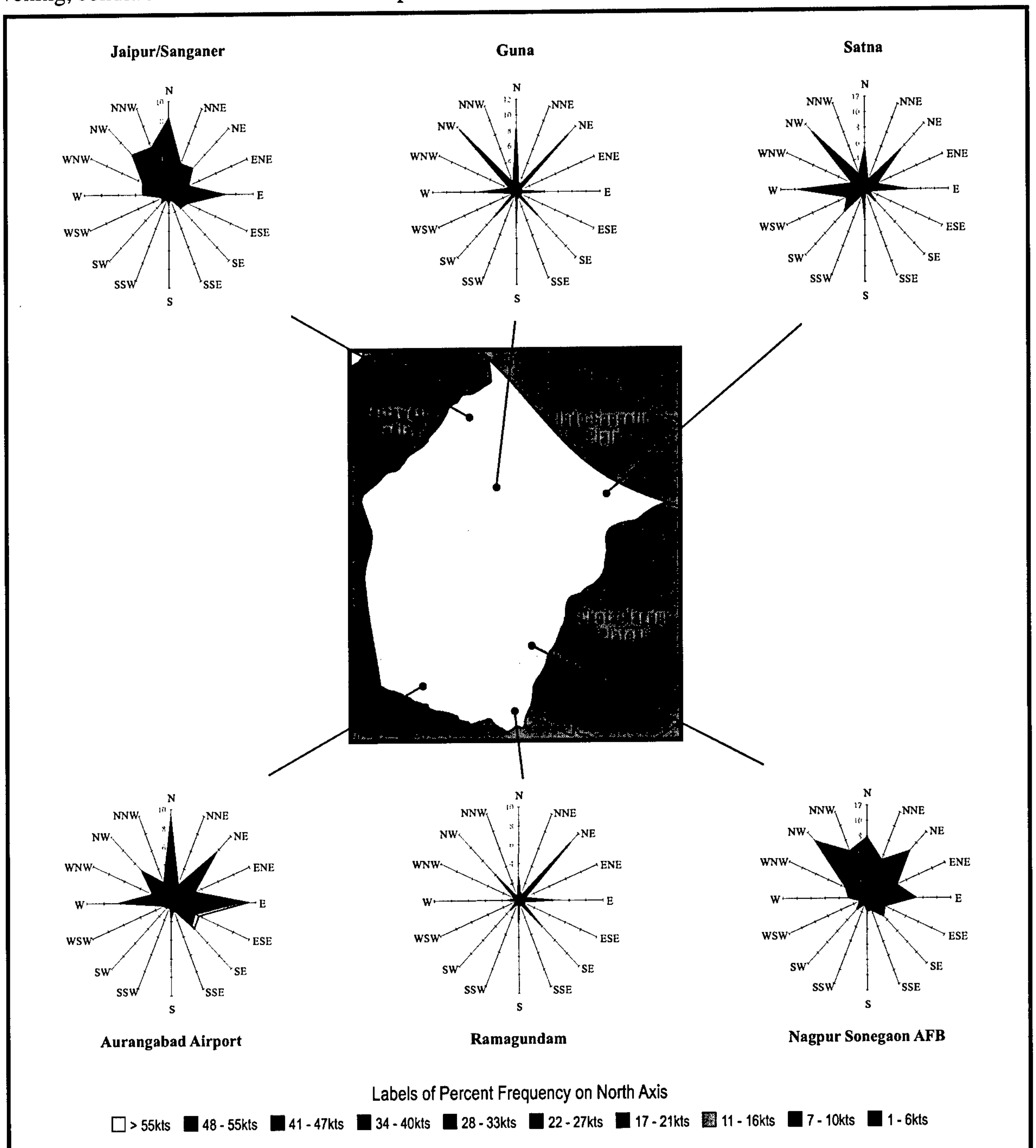


Figure 6-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The upper-air winds are from the northeast and east up to 700 mb. Mean speeds are 15-25 knots. Winds at 500 mb are westerly at 25 knots. Maximum speed may reach 50 knots. The 300 mb winds are also westerly and increase in speed through the season. Winds are from the west at a mean speed of 30 knots, with maximum winds up to 60 knots. Figure 6-30 shows the upper-level winds for October in Aurangabad and Bhopal.

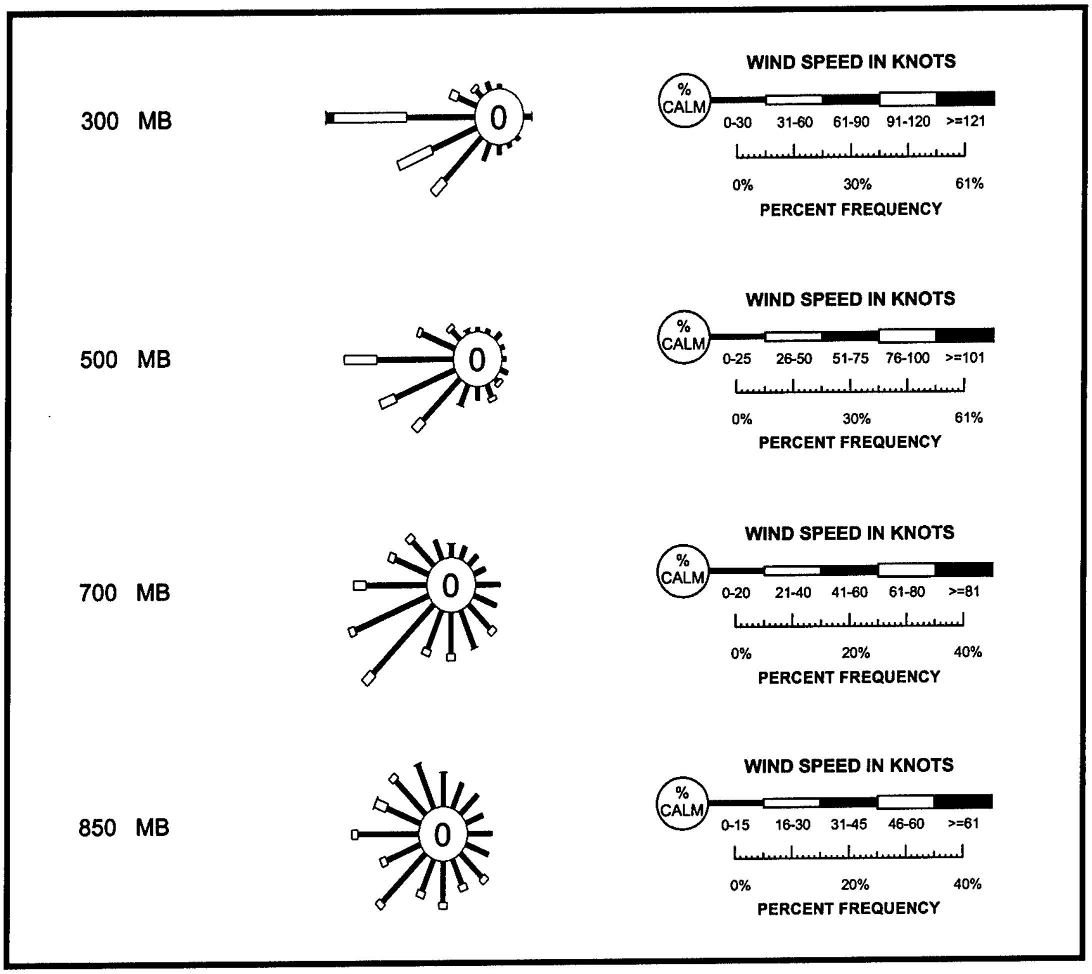


Figure 6-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Aurangabad and Bhopal.

Precipitation. There is a drastic decrease in precipitation. Terrain plays an important role in the distribution of rain over the region. In the rain shadow of the Western Ghats, the rainfall decreases sharply. The Satpura, Vindhya, and Aravalli Ranges are less significant barriers to precipitation. The average is 1-2 inches (25 to 51 mm) in October. By November, the average decreases to less than 1 inch (25 mm). The average number of days with precipitation is 4-6 days in October, and 1-3 days in November. Maximum 24-hour precipitation, averages 3-4 inches (76-102 mm) in October and decreases to 2-3 inches (51 to 76 mm) in November. On extremely rare occasions, as much as 6 inches (152 mm) can occur. Thunderstorms are rare but fairly uniform throughout the entire region. Two to three storms occur in October, and decrease to one a month in November. Hailstorms are rare. Figures 6-31 and 6-32 show the October mean precipitation amounts and seasonal precipitation and thunderstorm days, respectively.

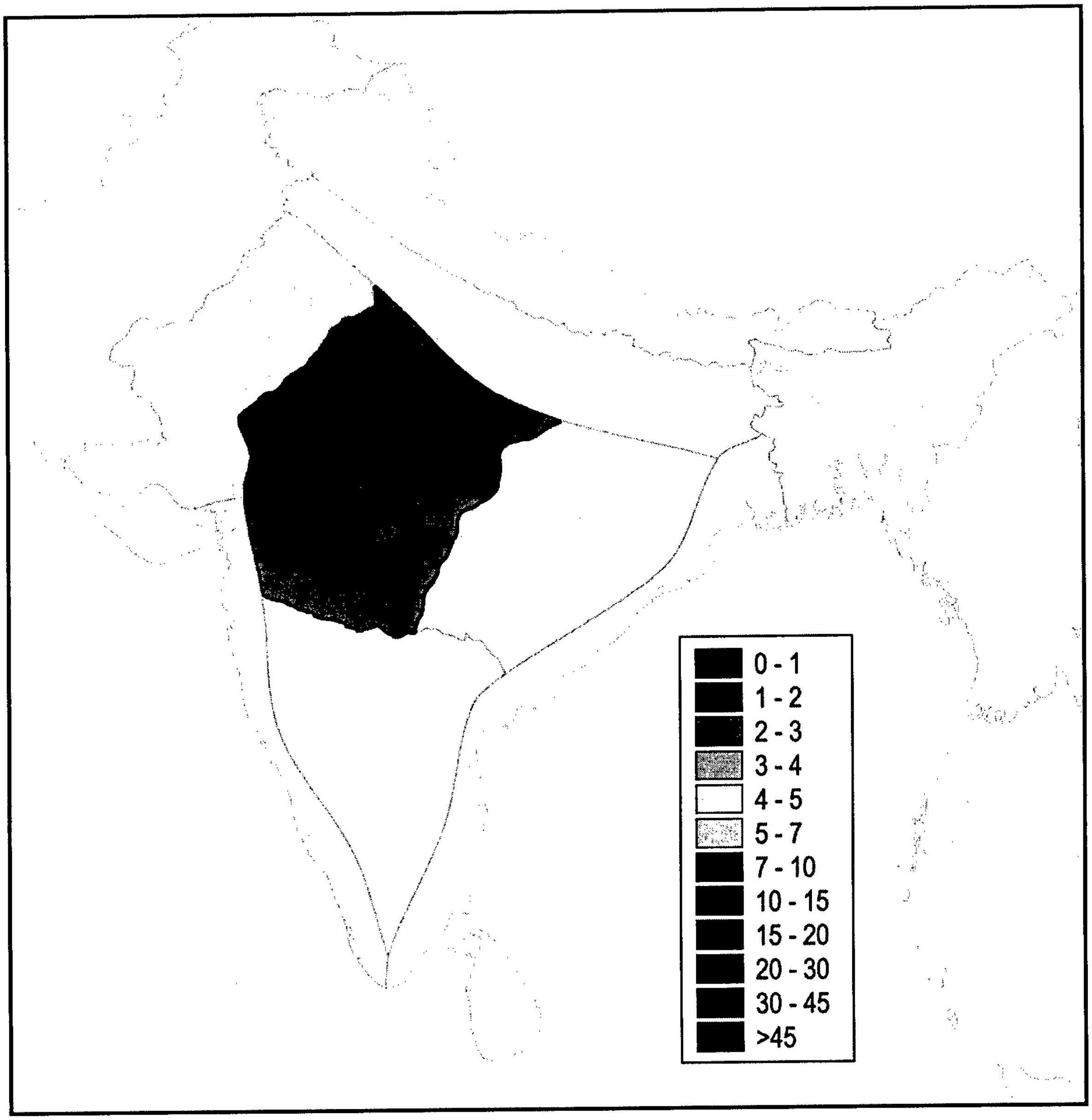


Figure 6-31. October Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

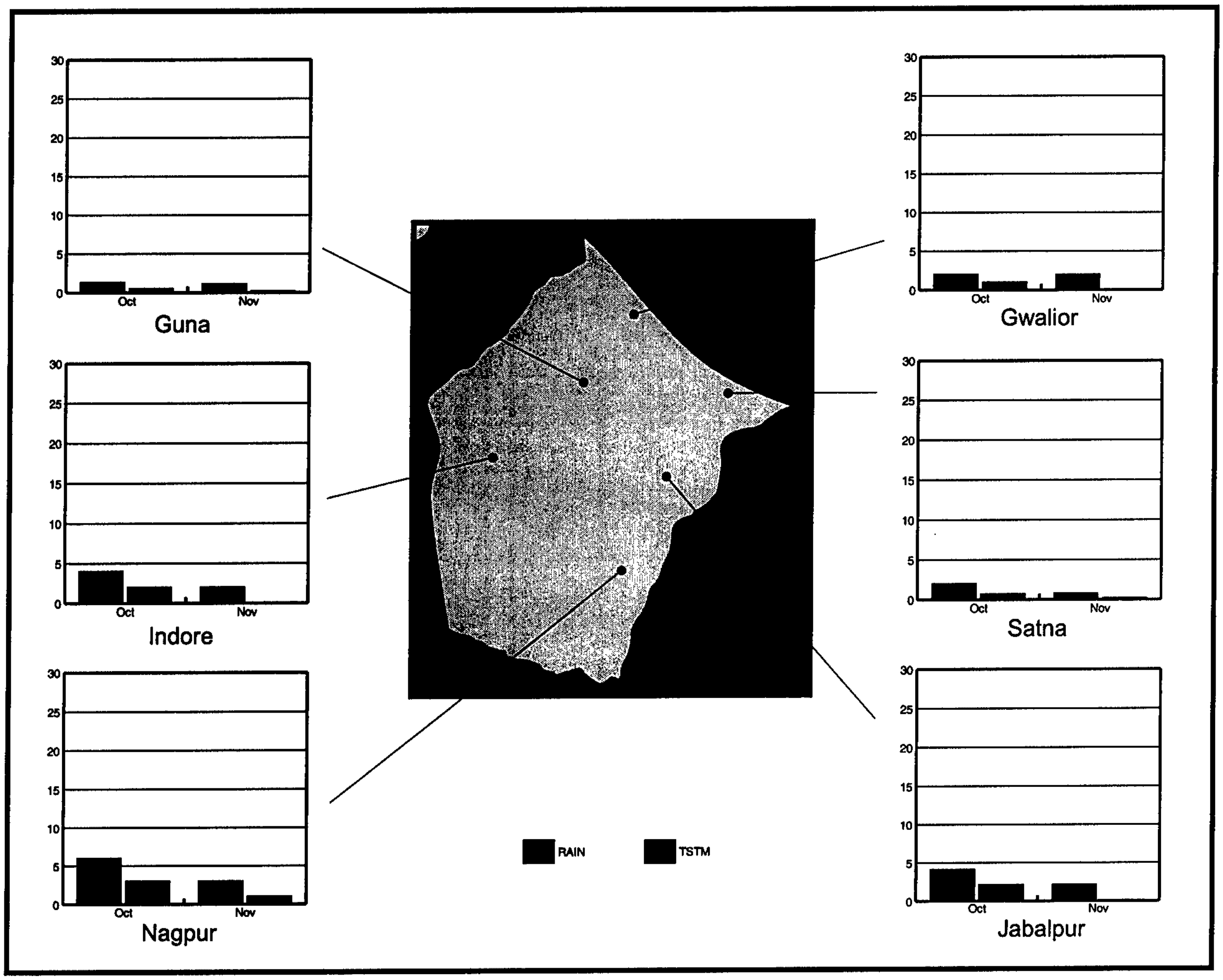


Figure 6-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. The retreat of the monsoon results in a decrease in cloud cover and brings a slight, short-term increase in temperatures. The fairly uniform temperatures decrease from October through November. The mean highs are 88° to 90°F (31°to 32°C) in October and 82° to 84°F (28° to 29°C) in November. Mean lows are 68° to 70°F (20° to 21°C) in October and 59° to 61°F (15° to 16°F) in November. During cold outbreaks, cooler air flows from the north-west from over the mountains of Afghanistan and brings lower temperatures. Extreme lows with these cold outbreaks range from 37° to 40°F (3° to 4°C). Extreme highs frequently top 100°F (38°C). The highest temperatures recorded at Kota was 106°F (41°C) in October, and at Akola in November, 104°F (40°C). The average relative humidity in the morning is 65 to 70% and decreases to 54 to 50% in the afternoon. Figures 6-33 and 6-34 show the respective October mean maximum and minimum temperatures.

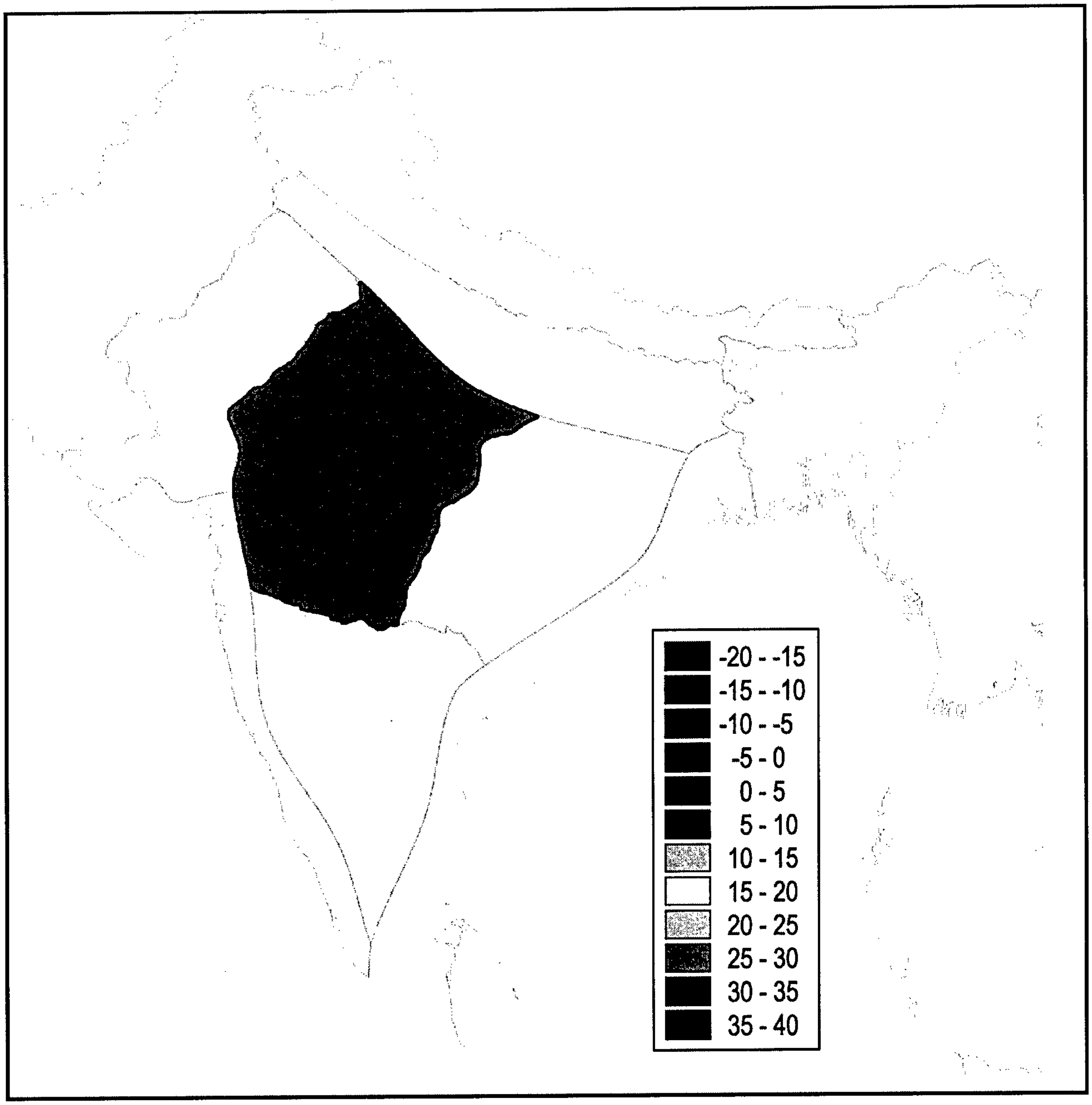


Figure 6-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in October. Daily high temperatures are often higher than the mean. Mean maximum temperatures during November may be lower.

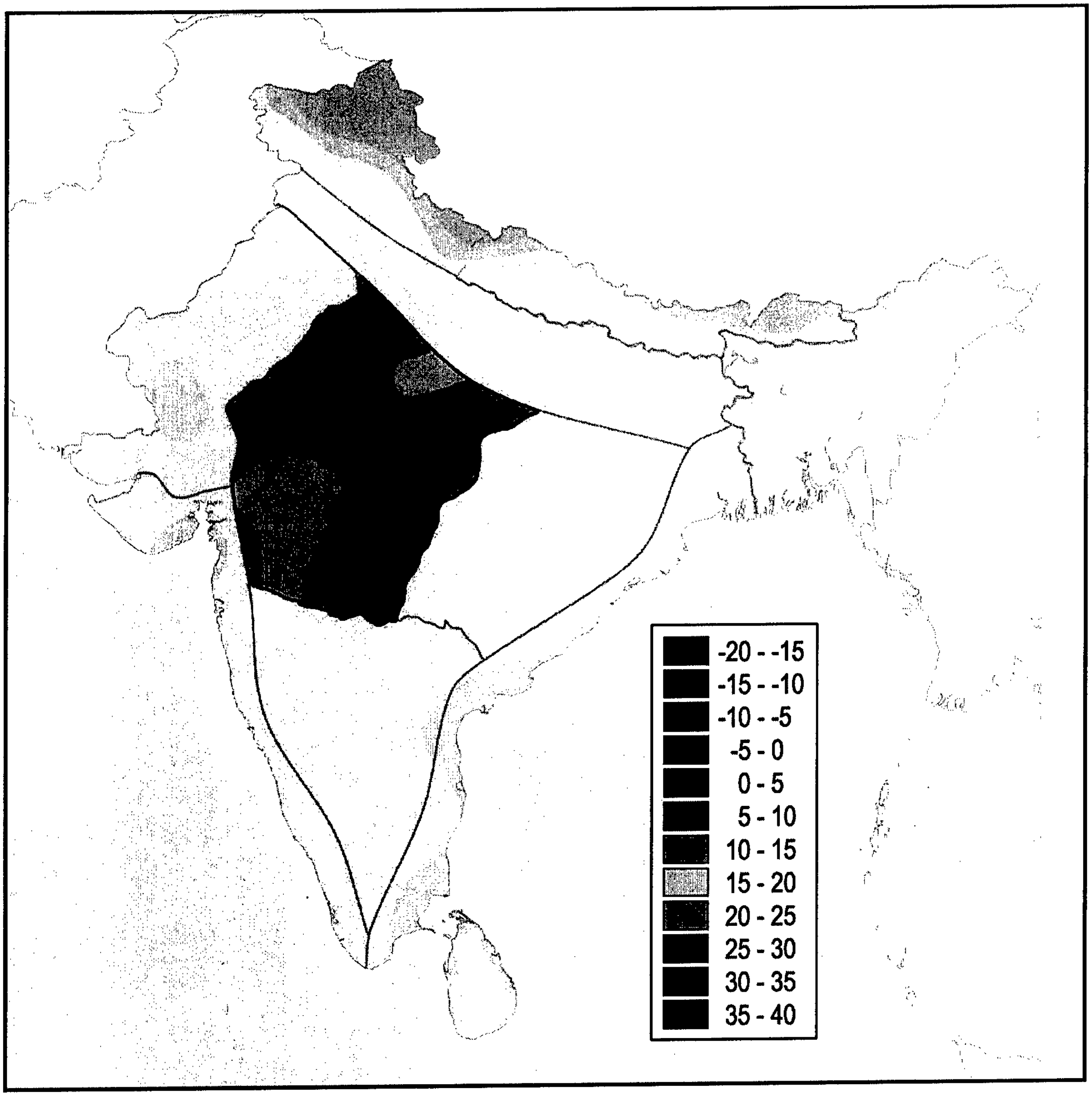


Figure 6-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in October. Daily low temperatures are often lower than the mean. Mean minimum temperatures during November may be higher or lower.

Chapter 7

SOUTH ASIAN ISLANDS

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for the South Asian Islands region.

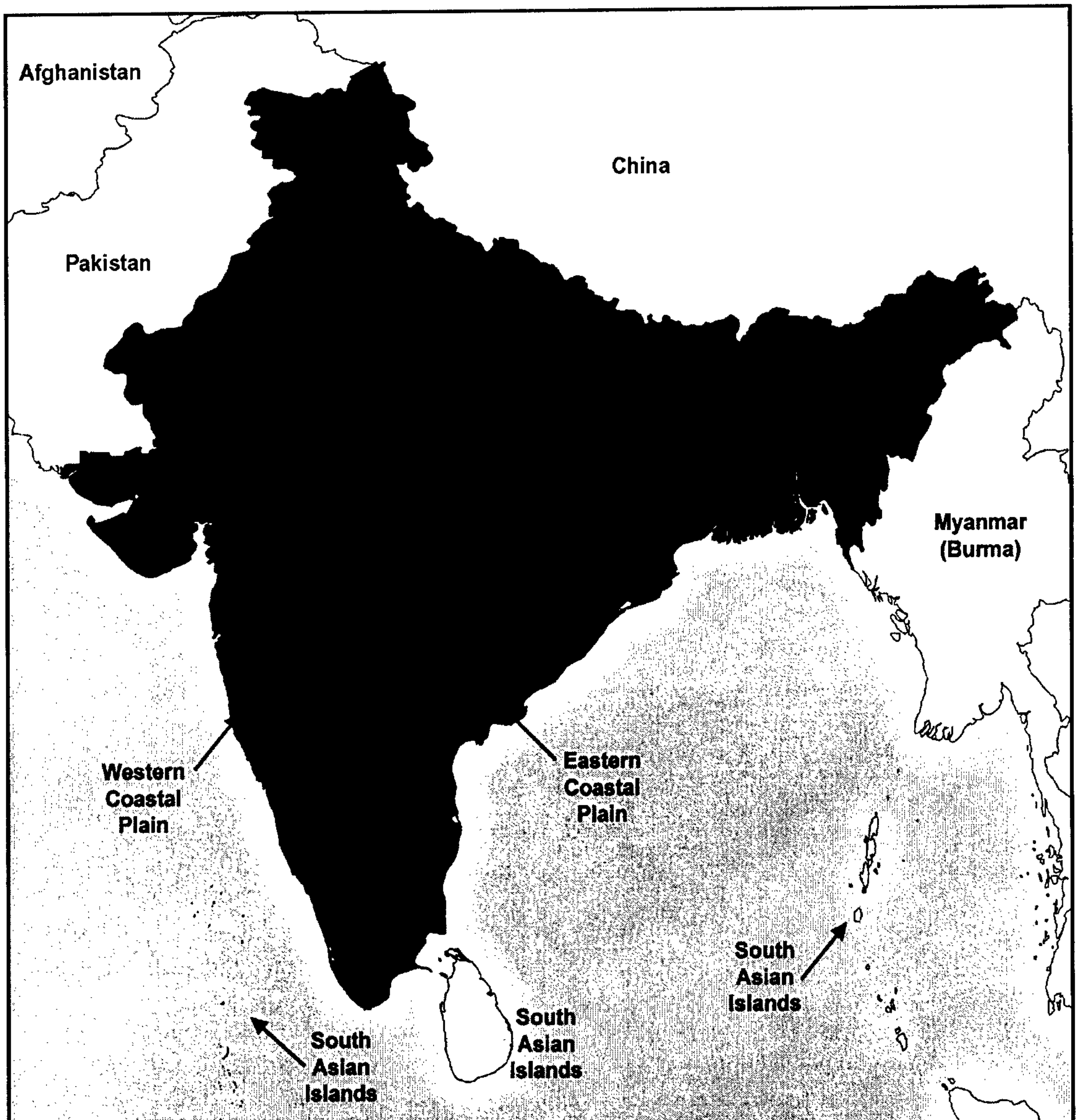


Figure 7-1. South Asian Islands. The area in yellow depicts the South Asian Islands region.

List of Topics

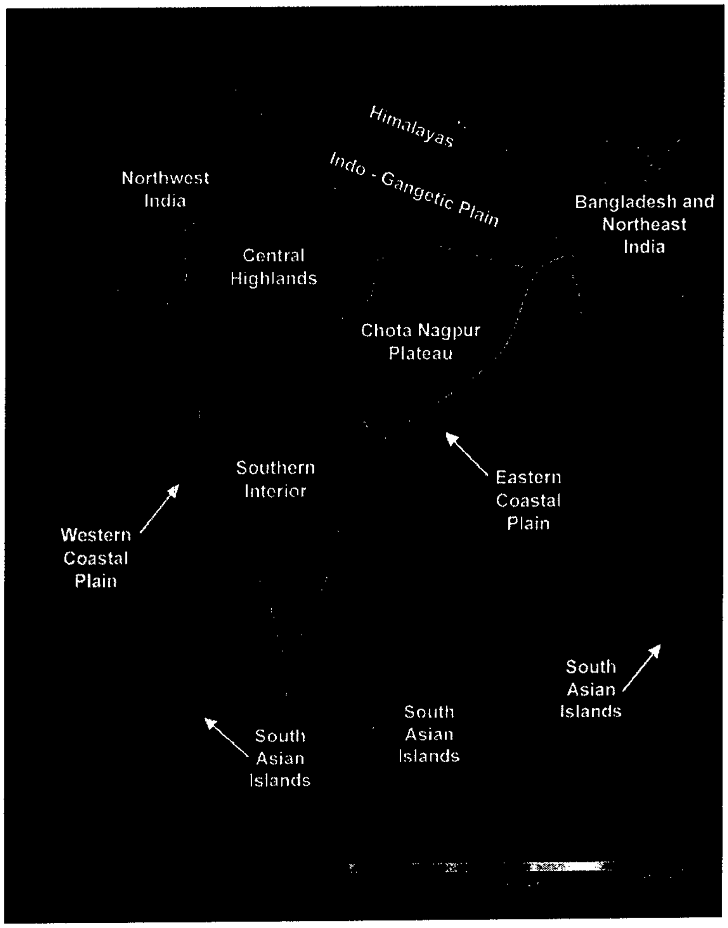


Figure 7-2a. Topography of South Asian Islands.

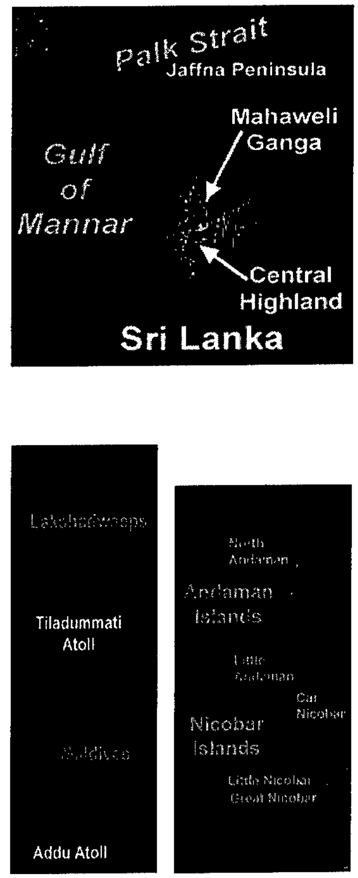


Figure 7-2b. Expanded View of Topography of South Asian Islands.

Topography

Area. This region includes Sri Lanka (formerly Ceylon), the Andaman Islands, the Nicobar Islands, the Lakshadweep Islands, and the Maldives. See Figures 7-1 and 7-2. Sri Lanka is just off the southeastern tip of the India peninsula. The Andaman Islands and the Nicobar Islands are in the southeastern corner of the Bay of Bengal. The Lakshadweeps and the Maldives are off the southwest tip of the Indian peninsula in the Arabian Sea and Indian Ocean.

Sri Lanka. Sri Lanka has three basic topographical zones: the highlands, the plains that surround them, and the coastal belt with many sandy beaches indented by lagoons. The island is connected to India by Adams Bridge, a string of shoals, near 9° N. Along the west coast, Palk Strait is north of the shoals, and the Gulf of Mannar is south of them. Sri Lanka is 270 miles (435 km) long and 140 miles (225 km) wide. The central part of the southern half of the island is a high, mountainous plateau called the Central Highland. Roughly 40 miles (65 km) long from north to south, it is approximately 60 miles (100 km) wide. Elevations range from over 2,000 feet (610 meters) to 6,000 feet (1,830 meters). The highest peak rises to 8,281 feet (2,524 meters). The high central ridges are flanked by two lower plateaus. To the west, Hatton Plateau is a deeply dissected series of ridges that slope down to the north. To the east, Uva Basin is made up of rolling, grassy hills traversed by deep valleys and gorges. On the north side of broad valleys north of the central ridges, Knuckles Massif has steep escarpments, deep gorges, and peaks that exceed 5,900 feet (1,800 meters). To the south of the central ridges, the Rakwana Hills are parallel ridges with several peaks over 4,600 feet (1,400 meters). To the southwest,

the Sabaragamuwa Ridges, oriented east-west, rise gradually from the plain to merge with the Central Highland. From the high part of the island, a lowland plain slopes gently down in all directions to the sea. Elevations slope down from 650 to 100 feet (200 to 30 meters). The Mahaweli Ganga (river) is the largest river on the island. It flows 210 miles (335 km) north from the central mountains to empty into Koddiyar Bay just south of Trincomalee. Many rivers lace the island; all radiate from the highland. In the north, Jaffna Lagoon, an east-west oriented body of water, nearly separates Jaffna Peninsula from the main land mass. It is a brackish mix of fresh and salt water fed by rivers that flow north from the highlands. Puttalam Lagoon, on the west-central coast around 8° N, is the second largest lagoon after Jaffna Lagoon. It is one of a chain of lakes that line the west coast from 6° 10' N to the lagoon. It is one of several with an outlet to the sea that allows salt water to mix with fresh. A chain of lakes also lines the east coast from 7° N to the north end of the island. Senayake Samudra reservoir, 7° 10' N, 81° 30' E, is the largest man-made lake on the island. Many lakes dot the lowlands that surround the south Central Highland.

Andaman Islands. These islands are in the Bay of Bengal southwest of Myanmar (formerly Burma) and are the northern section of the same chain of islands that contains Sumatra. The Andaman Sea separates the islands from Myanmar. The northern-most island is Landfall Island and the southern-most is Little Andaman. In between, the largest land mass of the group is in three pieces so close together, they appear to be one island. They are North Andaman, Middle Andaman, and South Andaman. Ritchie's Archipelago is on the east side of Deligent Strait, across from South Andaman. There are many small islands around the larger islands, many ringed by coral. All the islands in the group have low hills interspersed with lowlands. The hills are 1,000-1,700 feet (300-500 meters) tall on North, Middle and South Andaman and 400-700 feet (120-210 meters) tall on the other islands. A few hills reach 2,400 feet (730 meters) on North Andaman. All the islands are heavily vegetated. None are large enough to have significant rivers or lakes.

Nicobar Islands. These islands are south of the Andamans and part of the same chain that includes Sumatra, Java, and the Lesser Sundas. They lie between the Andamans and Sumatra. The Bay of Bengal laps the western coasts and the Andaman Sea laps the east coasts. Composed of three groups, the Nicobars extend from Great Nicobar Island in the south to Car Nicobar in the north. All the islands are heavily vegetated. Little Nicobar Island and Great Nicobar Island are almost entirely forested. From north to south, the elevation of the hills rise progressively from 400-600 feet (120-180 meters) on Car Nicobar, to 600-800 feet (180-240 meters) on Teressa Island, 400-800 feet (120-240 meters) on Camorta Island and Katchall Island, 1,400 feet (425 meters) on Little Nicobar Island, and to 2,100 feet (650 meters) on Great Nicobar Island. Tiny islands dot the area, most less than 15 feet (5 meters) above sea level. Most of the islands are surrounded by coral. None are large enough to have significant rivers or lakes, although the larger islands have streams that drain the highlands.

Lakshadweep Islands. Sometimes called the Laccadive Islands, these islands are off the southwest tip of peninsular India. The southeastern corner of the Arabian Sea, the Laccadive Sea, separates the islands from the peninsula. The islands are coral atolls that rest atop a north-south oriented submarine ridge in the sea. Mean elevation is 3-5 feet (1-1.5 meters). There are no hills, rivers, or lakes on any of the islands.

Maldives. These islands are in the Indian Ocean farther south on the same submarine ridge as the Lakshadweep Islands top. Composed of approximately 1,200 coral atolls in a double chain of 27 atolls, the Maldives reach from Addu Atoll, just south of the equator, to North Tiladummati Atoll, just south of 7° N. Most atolls consist of a large, ring-shaped coral reef that supports numerous small islands. Most islands are 3-5 feet (1-1.5 meters) above sea level, the highest is 10 feet (3 meters) above sea level. There are no hills, rivers, or lakes on any of the islands. Although some of the atolls are roughly 30 miles (50 km) long from north to south and 20 miles (30 km) wide from east to west, no single island is longer than 5 miles (8 km). Each atoll has 5-10 inhabited islands and 20-60 uninhabited ones. Several atolls consist of one large island surrounded by a steep coral beach. Fua Mulaku, in the middle of the Equatorial Channel, is an example of this type of atoll.

Major Climatic Controls

Asiatic High. This thermal high develops over Asia and dominates the weather over the entire continent from November to April. The vast pool of cold, dry air it pushes outward in all directions is a key part of the northeast monsoon. Because of the continental source of the air, the weather associated with it is dry.

Australian High. This thermal high sets up over Australia during Southern Hemispheric winter (May through October). It helps smooth the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ). The outflow from this high helps to push the equatorial trough (ET) northward to produce the south Asia southwest monsoon season.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon (November to April). This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area.

North Pacific High. This is a major player in the monsoon seasons of South Asia. It shifts north and west in Northern Hemisphere summer (May through October) and east and south in the winter (November to April). The high is linked to the position of the ET, which marks the boundary between the northeast and southwest monsoons.

South Indian Ocean (Mascarene) High. This year-round high-pressure system shifts north and south. During Southern Hemisphere winter, it provides cross-equatorial flow from May to October (reflected in the Somali jet and the equatorial westerlies). This warm, moist flow helps push the ET northward.

Asiatic Low. This is a thermal low that replaces the Asiatic high during Northern Hemisphere summer. The land heats, and the consequent low draws in air.

Australian Low. This thermal low lies over Australia during Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), draws the ET south of the equator, and brings drier weather to South Asia.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the Bay of Bengal and is a southwest monsoon feature. Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for the development of monsoon depressions. Easterly waves refire when they encounter the trough and some develop into disturbances or depressions. Of all the islands, Sri Lanka is the most vulnerable to these storms.

Monsoon Climate. South Asia has distinct rainy and dry seasons. Under the northeast monsoon, the whole region is drier, but the islands get periodic rain all season. Sri Lanka, the Andamans, and the Nicobars get rain on windward slopes during the northeast monsoon. Under the southwest monsoon it is rainy. Onset of the rainy season varies by latitude and terrain, but it usually occurs between mid-May and late June. It lasts from early April to mid-December on the Maldives and late May to late November on Sri Lanka.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough in this region, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north (May through October), the southwest monsoon takes over in South Asia. When it shifts south (November through April), the northeast monsoon assumes control.

Bay of Bengal. This large bay is the primary breeding ground for tropical storm systems. Most of the rainfall in this area occurs from storms that develop along the ET, the India-Myanmar trough, or from other mechanisms. The northern half of the bay is more active than the southern half, but storms develop here year-round. The most active times are in October-November (maximum activity) and April-May (secondary maximum). Storms tend to come ashore on the east coast of the peninsula then recurve northward. Of all the islands, Sri Lanka is most vulnerable as its northern end is under a favored storm track. The Lakshadweeps get the remnants of storms after they cross the Indian peninsula. The storms do not regenerate much over the Arabian Sea before they reach the western islands.

Special Climatic Controls

Tropical Easterly Jet (TEJ). This jet exists only during the southwest monsoon season (May through October). An upper level jet that overlays the low-level westerlies, it provides an outflow mechanism for disturbances that develop below it. The heaviest precipitation in South Asia occurs directly beneath the TEJ. The Bay of Bengal and the Arabian Sea are both under the TEJ. The Bay of Bengal is well known to be a prime area for the development or regeneration of monsoon depressions, tropical cyclones, tropical waves, tropical vortices, and mesoscale convective complexes. The TEJ is an important element in the process.

Somali Jet (Low-Level Jet). Also known as the East African low-level jet, this jet exists during the southwest monsoon season and is a key transport for air from the Southern Hemisphere into the Northern Hemisphere. It has been suggested 50 percent or more of the cross-equatorial flow from the Southern Hemisphere into the Northern Hemisphere is moved by this jet. It is created when outflow from the South Indian Ocean high flows toward the thermal low pressure over northern Africa (May through October). The western edge of the outflow air mass piles up against the eastern slopes of the high mountains of the eastern African coast. The result of this squeeze is a terrain-induced zone of tight pressure gradient and the jet develops there. The Somali jet is a key element in the development of the equatorial westerlies that dominate the southwest monsoon season.

Equatorial Westerlies. These winds exist during the southwest monsoon season. These large-scale, low-level winds are a result of a combination of factors. Outflow from the South Indian Ocean high (from the southeast) flows toward the thermal low over northern Africa (to the northwest), but the high mountains on the eastern coast of Africa are significant barriers that force a deflection. The Somali jet then helps transport the air into the northern hemisphere. The air mass is recurved eastward and these westerly winds take over throughout the monsoon region.

Tibetan Anticyclone. This Northern Hemisphere, southwest monsoon upper-air feature sets up in the zone between the deep easterlies that reach almost to the foot of the Himalayas by July and the deep westerlies of the Northern Hemisphere midlatitudes. Formed above the thermal low of the Tibetan plateau, it is important to the climate during this season because tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. Also, since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought. For a more detailed descriptions, review Chapter 2.

Easterlies. This deep east wind band persists year round in the low latitudes. It shifts north and south with the sun. During the southwest monsoon, it shifts north and widens to encompass a larger area. Thanks to a number of factors, it also strengthens enough to develop the tropical easterly jet, a broad ribbon of higher winds that strongly influence the development of monsoon rains, tropical disturbances of all intensities, and monsoon depressions. During the northeast monsoon, the band of easterlies narrows and shifts south. At the height of the northeast monsoon, the easterlies are held south of 5° N.

Easterly Waves. During the southwest monsoon season (May through October), easterly waves are known to help fire the formation of monsoon depressions over the northern Bay of Bengal. They travel from east to west in the deep easterlies and last 1-2 weeks. They are accompanied by clear weather ahead of the trough and heavy showers and thunderstorms behind. They sometimes create cyclonic vortices off shore the southwestern end of the Indian peninsula and can cause thunderstorms and rainshowers over Sri Lanka and the southern tip of the peninsula. The Andamans, Nicobars, Lakshadweeps and northern Maldives all feel the effects of easterly waves, but they are blunted by the passage over land east of these islands. The intensity and frequency of occurrence of easterly waves are indicators of the strength of the monsoon.

Cyclonic Storms. Monsoon depressions, tropical cyclones, tropical waves, tropical vortices, mesoscale convective complexes, and cloud clusters are all types of cyclonic storms of varying scales of intensity and size. Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Some travel into the area from the west (western disturbances). Some of these factors

have influence during the southwest monsoon season, such as the Tibetan anticyclone, easterly waves and the India-Myanmar trough. The ET influences the weather during the transition periods when it moves through the area. During the northeast monsoon, western disturbances and tropical vortices are the bigger players in the development of weather systems. Regardless of when they develop, some storms can be fierce. Because the waters of the bay are so confined, however, storms do not have the opportunity to develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation, cause extensive flooding and loss of life, and destroy crops and property. Storms tend to come ashore on the peninsular east coast of India then recurve northward. The heaviest precipitation falls in the southwest through south quadrants of the storms.

Monsoon Depressions/Low-Pressure Systems. These are important synoptic-scale disturbances that make major contributions to the monsoon circulation in organizing low-level convergence. During the southwest monsoon season, these storms move along the ET (monsoon trough) toward the north. They normally form in the Bay of Bengal north of 18° N and move west-northwest across India. They bring heavy rains, especially in the southwest quadrant of the storm. These systems rarely develop into tropical cyclones and are associated with a series of low-pressure systems and easterly waves in the northern Bay of Bengal. The strongest winds are in the southern sector of the storms thanks to augmentation by the equatorial westerlies. Approximately 80 percent of the total number of depressions that form in the South Asia region are monsoon depressions. The majority of monsoon depressions and other cyclonic storms form in the Bay of Bengal, as opposed to the Arabian Sea, and most of them form in the northern part of the bay.

Land/Sea Breeze. These winds are caused by diurnal land/sea temperature differences. By day, the sea is cooler than land and the wind blows onshore. Onshore winds advect moisture upslope and create rainshowers and thunderstorms over higher elevations inland. This is especially common on Sri Lanka. Cloud cover spreads out over the lowlands windward of the higher ground. By night, the temperature difference reverses and the winds become offshore. Cooler, drier, offshore winds converge with the moist, warmer air over the sea and can create lines of rainshowers and thunderstorms over the water, especially near the larger islands, like Sri Lanka. Monsoonal flow can enhance sea breezes or damp them, which depends on the position of a site relative to large-scale monsoonal flow.

Hazards for All Seasons

Tropical Cyclones. Sri Lanka is most vulnerable to tropical cyclone activity. The southern storm track in the Bay of Bengal lies just north (across the southern Indian peninsula). The north end of the island, especially the northeastern coast, is affected. Storms sometimes make landfall on the island itself. Either way, heavy rains, high winds, and thunderstorms all occur on Sri Lanka. The Nicobars and Andamans are too far east for these storms and the Maldives are too far south. The Lakshadweep Islands are on the other side of the peninsula and the storms do not have time to regenerate before crossing the islands. Nevertheless, they still get heavy weather and strong winds with the diminished storms. The peak season for tropical cyclones is in October and November, when the southern track is the more active of the two in the Bay of Bengal, but the official season is from June to November. A storm has occurred in every month of the year.

Thunderstorms. Thunderstorms in Sri Lanka are frequent and often violent. They are more frequent during the transitions seasons but may occur at any time of the year. Severe turbulence, heavy icing, frequent lightning, strong downrush winds, gusty surface winds, and occasionally hail, accompany the storms.

Turbulence. Turbulence is a year round threat over the mountainous islands. Winds that blow across the mountains will create moderate-severe turbulence over the crests and as much as 50 miles (80 km) downwind. Turbulence may extend as high as 15,000-20,000 feet. Rising air currents from intense surface heating will cause light-moderate turbulence from the surface up to 6,000 feet. During the southwest monsoon, expect moderate-severe turbulence at 25,000-35,000 feet in the vicinity of the tropical easterly jet.

Aircraft Icing. The freezing level is at 14,000-16,000 feet all year. Except in thunderstorms, aircraft icing is not a threat below this level. The -20°C isotherm is near 25,000 feet all year, so icing will be encountered in clouds between about 15,000 feet and 25,000 feet. In thunderstorms, icing is probable to much higher levels.

Flooding. Vast amounts of rainfall in a very short time in the southwest monsoon throughout the region and over northern Sri Lanka in the northeast monsoon. On the mountainous islands, flash flooding in narrow valleys occurs with little or no warning. For example, large areas of the low lands on both sides of the Sri Lankan central mountains may be inundated for days at a time during and after prolonged periods of heavy rain.

Heat-Related Hazards. Continuous high temperatures and humidity can be debilitating and dangerous. The web-bulb globe temperature or comfort indices should be closely monitored. Dehydration, heat stroke, and sun stroke are threats throughout the year.

Winter

General Weather. In winter, the northeast monsoon dominates. The massive thermal high over Asia is a driving force that pushes the ET south of the equator. The thermal low over Australia helps pull it southward. Although this is a dry season, windward Sri Lanka and the Maldives get considerable rain. The Maldives have no prolonged periods of dry weather, particularly around Male. Rather, they have two rainy seasons with brief transitions. Winter rains are brought by the ET, which moves into the vicinity at the southern rim of the northeast monsoon. February is the only month of the year rainfall decreases sharply as the northeast monsoon is farthest south in that month. The windward slopes of Sri Lanka get considerable upslope precipitation thanks to the long, over-water trajectory the northeast winds take across the Bay of Bengal. The deep band of easterlies that dominate upper-air flow in the southwest monsoon are held south of 5° N and do not influence the weather in this region nearly as much as the westerlies that take over in this season, except in the Maldives.

Onset of the northeast monsoon, or winter, season varies within a general frame that depends on latitude and terrain. The ET retreat southward marks the onset of the season. It occurs first on Sri Lanka, the Lakshadweeps, and the Andamans and last on the Maldive islands in the Addu Atoll. Usually, the ET does not move south of the Addu Atoll, south of the equator, until mid-December, and it oscillates back and forth across them through the season. The northeast monsoon brings northeasterly winds and more stable conditions to the region.

Tropical cyclones and other cyclonic storms are less likely than during the southwest monsoon, however, the storm season extends to November. Although the rate drops off sharply after November, there is an incidence of at least one storm in every month of the year. The minimum number occurs in February, when the northeast monsoon is at its greatest strength. Sri Lanka and the Lakshadweep islands are most vulnerable, especially Sri Lanka. Storms make landfall on the peninsula just north of the island or strike the island itself. Either way, they bring high winds, heavy rains, and storm surges to Sri Lanka. Partly sheltered by the Indian peninsula, the Lakshadweeps get heavy rains but less powerful winds than Sri Lanka. The Maldives are too far south for tropical cyclones. The Andamans and Nicobars are too far east for anything but late season easterly waves that track over Malaysia.

Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Western disturbances, easterly waves, and vortices also grow into storms over the warm waters of the bay. While some of these factors have a greater influence during the southwest monsoon season, such as easterly waves and the India-Myanmar trough, the early and late parts of the northeast monsoon season still experience weather stirred by them. Regardless of when they develop, the storms can be fierce. Because the waters of the bay are so confined, however, storms do not develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation, cause extensive flooding and loss of life, and destroy crops and property.

Sky Cover. Figure 7-3 shows the seasonal percent frequency of ceilings below 5,000 feet for selected South Asian Islands locations.

Sri Lanka. The great majority of the island has little low cloud; the most is in December and the least in February in a steady, downward progression. The eastern side of the island has more cloud cover than the western side as it is windward to northeast monsoon flow. The Central Highland windward slopes are the cloudiest places on the island. Eastern locations have ceilings below 5,000 feet 25-35 percent of the time in December, 15-25 percent of the time January, and 5-15 percent of the time in February. The west side, with exceptions, has them 10 percent of the time in December with afternoon maximums of 20 percent of the time. By January, most western sites have ceilings below 5,000 feet 5-10 percent of the time with the maximum in the afternoons. Puttalam, on the inland shore of Puttalam Lagoon, experiences ceilings below 5,000 feet 30-40 percent of the time in afternoon rainshowers but only 5-10 percent of the time the rest of the day. A narrow strip of land separates the lagoon from the Indian Ocean. The afternoon sea breeze moves across the narrow strip of land, meets the monsoon flow and creates a sea breeze front that produces afternoon convection at Puttalam. In the Central Highland, ceilings below 5,000 feet occur

40-50 percent of the time most of the day in December with a maximum of 70 percent of the time in the afternoons. By January, this rate drops to 20-30 percent of the time with afternoon maximums of 50 percent of the time. February is lower still, 15-25 percent of the time with maximum rates of 40 percent of the time in the afternoons. Except for the Central Highland, ceilings below 1,000 feet are rare. In the highlands, they occur 40-50 percent of the time in December, 20-30 percent of the time in January, and 10-20 percent of the time in February. In every case, afternoon rates are 10 percent higher than the norm for the rest of the day. Cloud cloaking occurs at elevations above the lifting condensation level (LCL).

Nicobars and Andamans. Morning ceilings below 5,000 feet occur 20-25 percent of the time in December and January and 10 percent of the time in February. In the afternoons, they occur 15-20 percent of the time in December and January and 5 percent of the time or less in February. Ceilings below 1,000 feet occur rarely.

Lakshadweeps and Maldives. Mean cloud cover in the northern half of the region is scattered, but the southern half of the region is broken in the vicinity of the ET. Most of the cloud cover is above 5,000 feet. In the Lakshadweeps, ceilings below 5,000 feet occur 5-10 percent of the time at all hours through the season. Ceilings below 1,000 feet are rare. In the Maldives, ceilings below 5,000 feet occur 10-15 percent of the time in the afternoons and roughly 5 percent of the time the rest of the day. Ceilings between 5,000 and 10,000 feet occur more often, 15-20 percent of the time in the afternoons and 10-15 percent of the time the rest of the day. Ceilings below 1,000 feet do not occur except in rainshowers for brief periods.

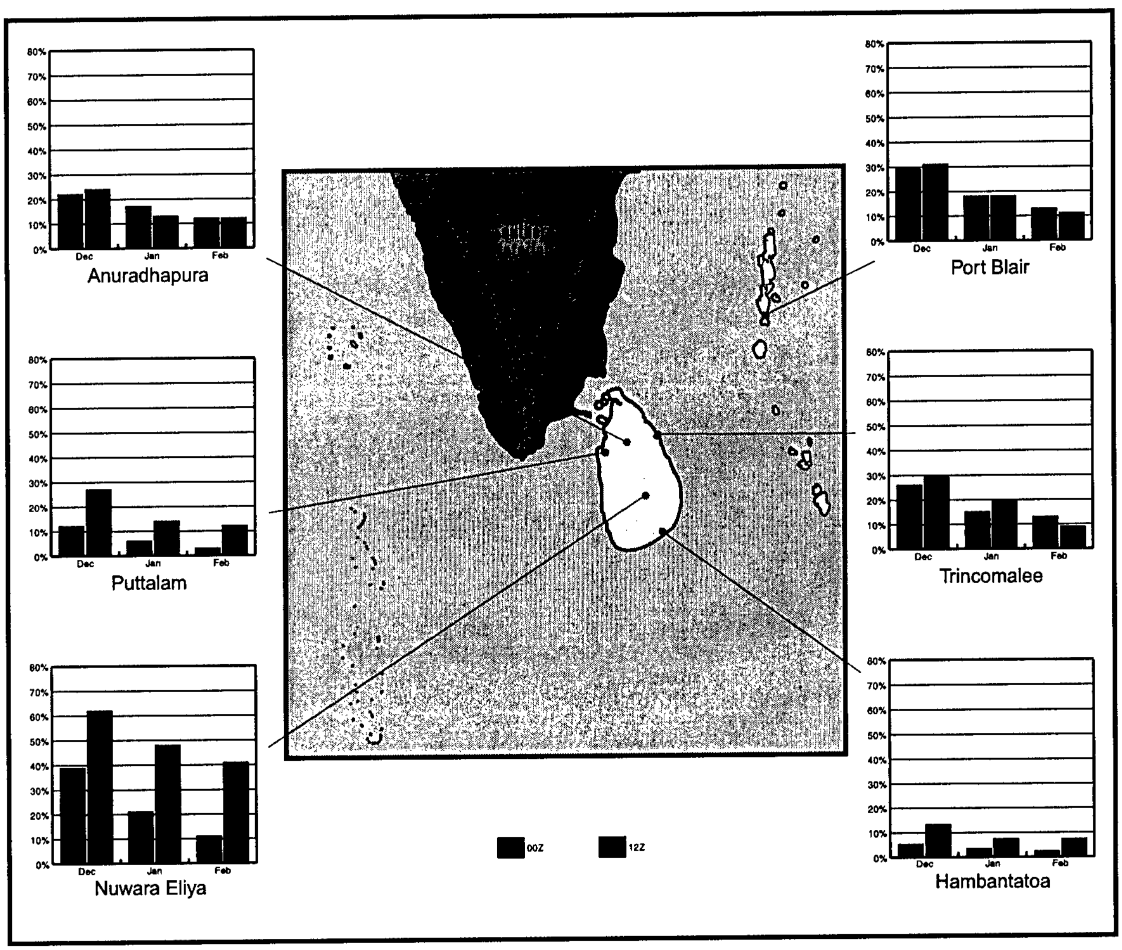


Figure 7-3. Winter Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Figure 7-4 shows the seasonal percent frequency of visibility below 21/2 miles (4,000 meters) for selected South Asian Islands locations.

Sri Lanka. Visibility is good, except during brief afternoon rainshowers. In the east, visibility is rarely less than 4,000 meters. In the west, it occurs 4 percent of the time, almost exclusively during the early morning hours. Visibility less than 1 1/4 mile (2,000 meters) occurs only with morning fog and then rarely. The Central Highland has poor visibility because of cloud cloaking. At Nuwara Eliya, visibility below 4,000 meters occurs 55-65 percent of the time on December evenings, 45 percent of the time at sunrise, 10-15 percent of the time from mid-morning to mid-afternoon, and 30 percent of the time from mid-afternoon to early evening. Conditions improve in January and February. Visibility below 4,000 meters occurs 30 percent of the time from mid-evening to sunrise and 10-15 percent of the time the rest of the day. Visibility below 2,000 meters occurs rarely even at Nuwara Eliya. At high elevations, visibility will be restricted in clouds that cloak the windward slopes above the LCL.

Nicobars and Andamans. Visibility below 4,000 meters occurs under 5 percent of the time at all hours through the season. The maximum rate is at sunrise. In the Andamans, sites at high elevations are likely to have poor visibility in cloud above the LCL. Visibility below 2,000 meters occurs rarely.

Lakshadweeps and Maldives. This area commonly enjoys good visibility at all hours.

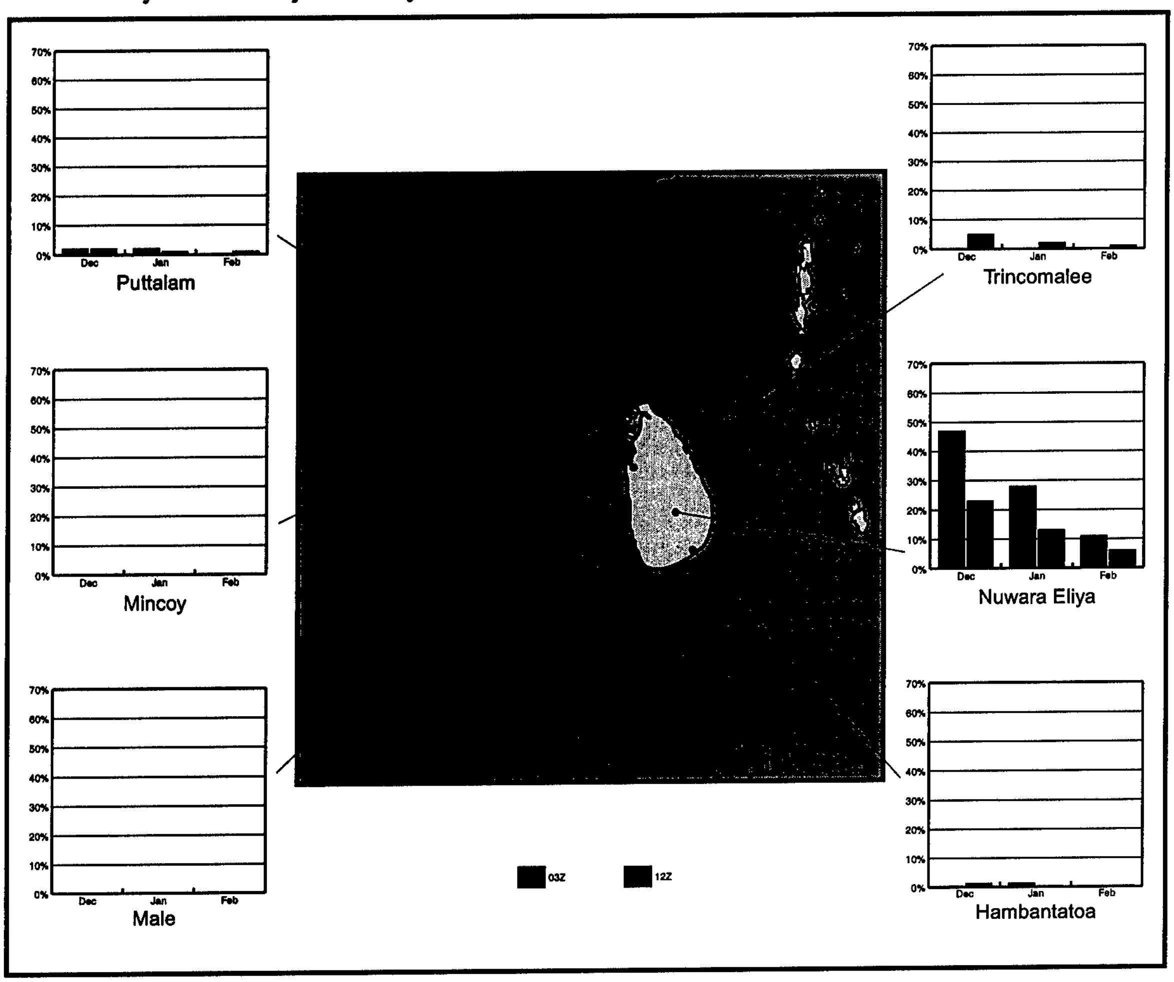


Figure 7-4. Winter Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. The January surface wind roses seen in Figure 7-5 reflect the winter northeast monsoon typical across the South Asian Islands.

Sri Lanka. Surface winds are generally from the northeast during this season. The wind speed is usually 5 to 10 knots. During rainshowers or thunderstorms, surface winds will gust to 20 or 25 knots. Speeds higher than 25 knots are uncommon, except at Hambantatoa, on the southeastern coast, where gusts above 30 knots occur. During the afternoon, the sea breeze on the east coast will enhance the monsoon flow. Speeds of 12 to 15 knots may occur for a few hours. On the southern half of the west coast, sea breeze winds are northwesterly or northerly during the afternoon. This is because the central mountains significantly block the monsoon winds and northeast winds overnight are caused more by drainage from the highlands than the northeast monsoon. In the central mountains, surface winds are strongly influenced by terrain. Nuwara Eliya, in a high valley between mountain ridges, experiences east or southeast winds during the northeast monsoon. Night calms occur far more on the southern west coast than anywhere except protected mountain valleys. On the west coast, overnight calms occur 25-35 percent of the time. During the day the rate drops under 5 percent of the time. In protected mountain valleys, calms occur 50-60 percent of the time at night and 20-30 percent of the time during the day.

Nicobars and Andamans. Surface winds are all but exclusively from the northeast at 5-10 knots at night and up to 15 knots during the day. East coast locations have occasional gusts to 25 knots. In the Nicobars, overnight calms are common on the larger islands with higher ground, but light winds blow all night on the small, low islands. On average, the larger islands have overnight calms 90-100 percent of the time. During the day, the rates drop to 10-15 percent of the time from Car Nicobar to Port Blair (on South Andaman). South of Car Nicobar and north of South Andaman, the rates of calms are higher, 55-75 percent of the time during the day on all the islands.

Lakshadweeps and Maldives. The winds blow from the north at 10-15 knots with gusts to 25 knots on the Lakshadweep Islands. Night calms occur 20-30 percent in the northern islands and 45-55 percent of the time in the southern islands. During the day, calms occur 5-10 percent of the time throughout the group. On the northern Maldives, the winds blow from the northeast at 10-15 knots with gusts to 25 knots. Calms are rare, especially on the northern islands. On the southern islands close to the equator, they occur 10-15 percent of the time at night and 5 percent of the time or less during the day.

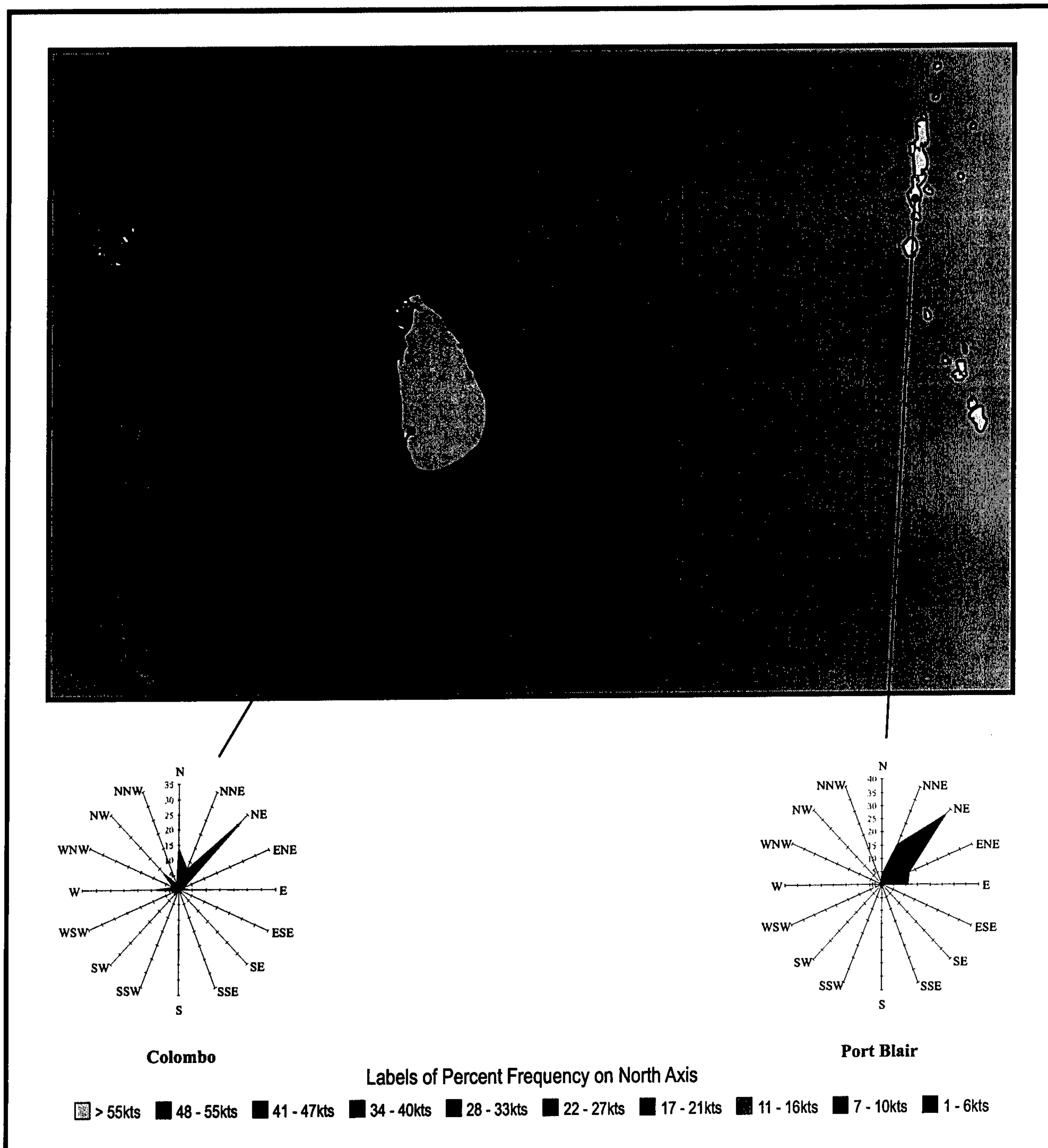


Figure 7-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Upper-air winds are northeast at 5,000 feet at an average of 16-30 knots. At 10,000 feet winds are east-northeast at 21-40 knots. Speeds increase to 26-50 knots from the east-northeast at 18,000 feet. At 30,000 feet winds are from the east to southeast at 31-60 knots. Figure 7-14 is a composite using Colombo, Port Blair and Gan and shows the typical January upper-air winds across the South Asian Islands.

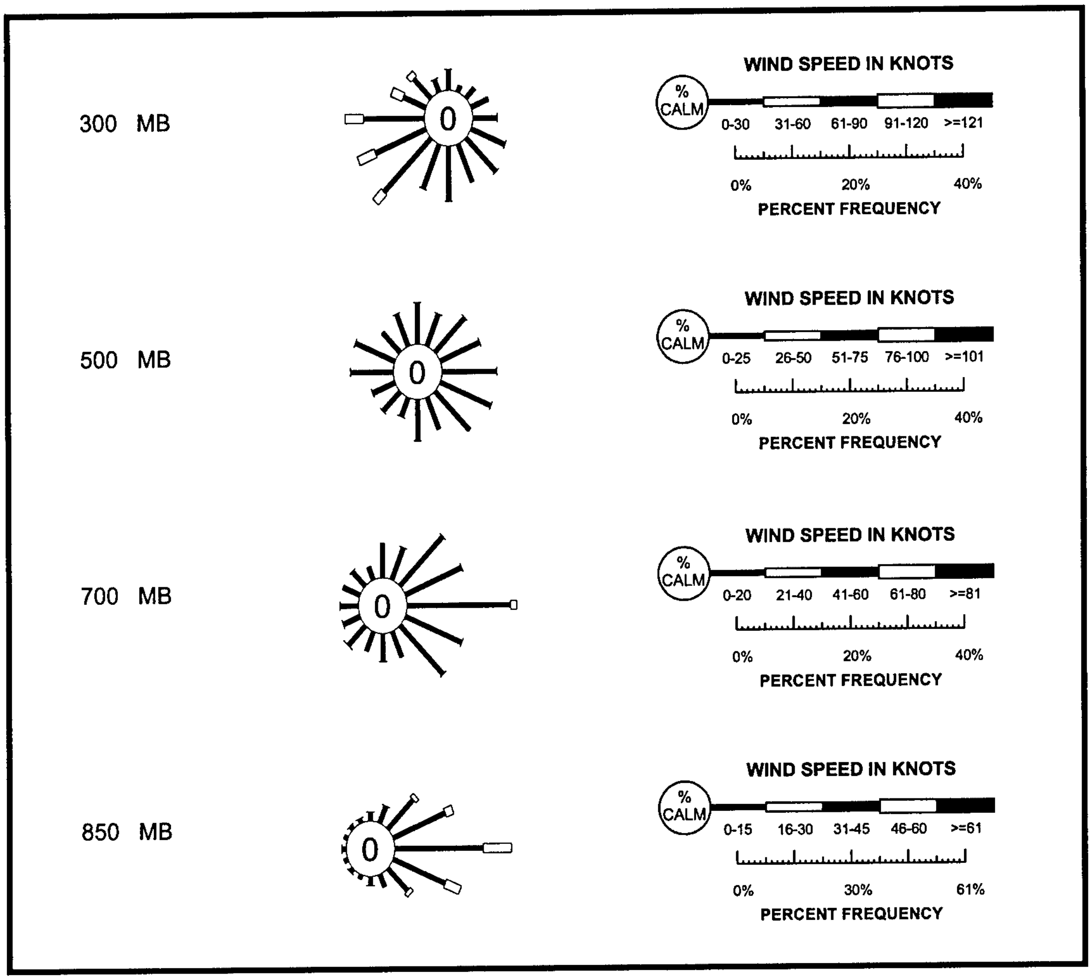


Figure 7-6. January Upper-Air Wind Roses. The composite (Colombo, Port Blair and Gan) wind roses depict wind speed and direction for standard pressure surfaces between 850 mb and 300 mb in the South Asian Islands.

Precipitation. Figure 7-7 depicts January mean precipitation amounts for the South Asian Islands, and Figure 7-8 shows seasonal precipitation and thunderstorm days.

Sri Lanka. December is the rainiest month of the season. In the east and in windward Central Highland sites, December averages 12-16 inches (305-406 mm) of rain, January gets 7-10 inches (178-254 mm), and February gets 2-4 inches (51-102 mm). In the west and in leeward Central Highland sites, December averages 5-7 inches (127-178 mm); January, 3-5 inches (76-127 mm); and February, 1-3 inches (25-76 mm). In the east, windward in the northeast monsoon, rain falls 18-22 days in December, but the west gets 10-15 days. In the Central Highland, windward sites get 18-22 days with rain and leeward sites get 8-12. Rain days decrease in January to 13-18 days in the east and the windward Central Highland and 5-10 days in the west and the leeward Central Highland. Rain decreases again in February to 5-8 days in the east and 2-4 days in the west. In the Central Highland, windward sites get 8-12 days with rain and leeward sites get 5-8. Thunderstorms occur most over the highlands. Lightning is often seen in the distance from many lowland sites. If distant thunderstorms were counted, the occurrence rates would be considerably higher. In December, thunderstorms occur 5-8 days island-wide, and in January and February, 1-4 days in the lowlands and 5-8 days in the highlands.

Nicobars and Andamans. Precipitation amounts decrease steadily through the season from 4-6 inches (102-152 mm) in December to 2-4 inches (51-102 mm) in January to 0.5-1.5 inches (13-38 mm) in February. Generally, the larger amounts fall in the Nicobars than the Andamans. Rain days drop steadily from 8-12 in December to 4-6 in January to only 2-4 days in February. The Nicobars have the most rain days. In this whole area, 1-2 thunderstorm days per month occur all season.

Lakshadweeps and Maldives. The Lakshadweeps are under northeast monsoon flow and get little rain. The average is 1-1.5 inches (25-38 mm) in December and January, and then, under 0.5 inch (13 mm) in February. It rains 1-2 days per month in December and January and less than 0.5 day in February. The rain most-often falls in convective precipitation. Thunderstorms occur 1-2 days per month in December and January, but rarely occur in February. Much of the Maldives are still under the southwest monsoon as late as the end of December and have an extended rainy season as a result. Year-round, the southern Maldives islands get more rain than the northern islands. The rain falls mainly as convective precipitation. The northern islands get 13-15 inches (330-381 mm) of rain on 10-15 days in December, 7-10 inches (178-254 mm) on 6-9 days in January, and then, drop to under 0.5 inch (13 mm) on 1-2 days in February as the ET moves south. In the southern Maldives, 5-7 inches (127-178 mm) of rain fall on 8-12 days in December, 8-11 inches (203-279 mm) on 9-14 days in January, and 14-16 inches (356-406 mm) on 14-18 days in February. In December, thunderstorms occur 5-7 days in the north and 3-5 days in the south. The northern islands get 2 thunderstorm days in January, but the southern islands get up to 10 days with thunderstorms because the ET is in the area. By February, the ET is at its southern-most position, and the northern Maldives get 1 day with thunderstorms or less. In the southern Maldives, 8-11 days with thunderstorms occur. Rainshowers will occur even more often.

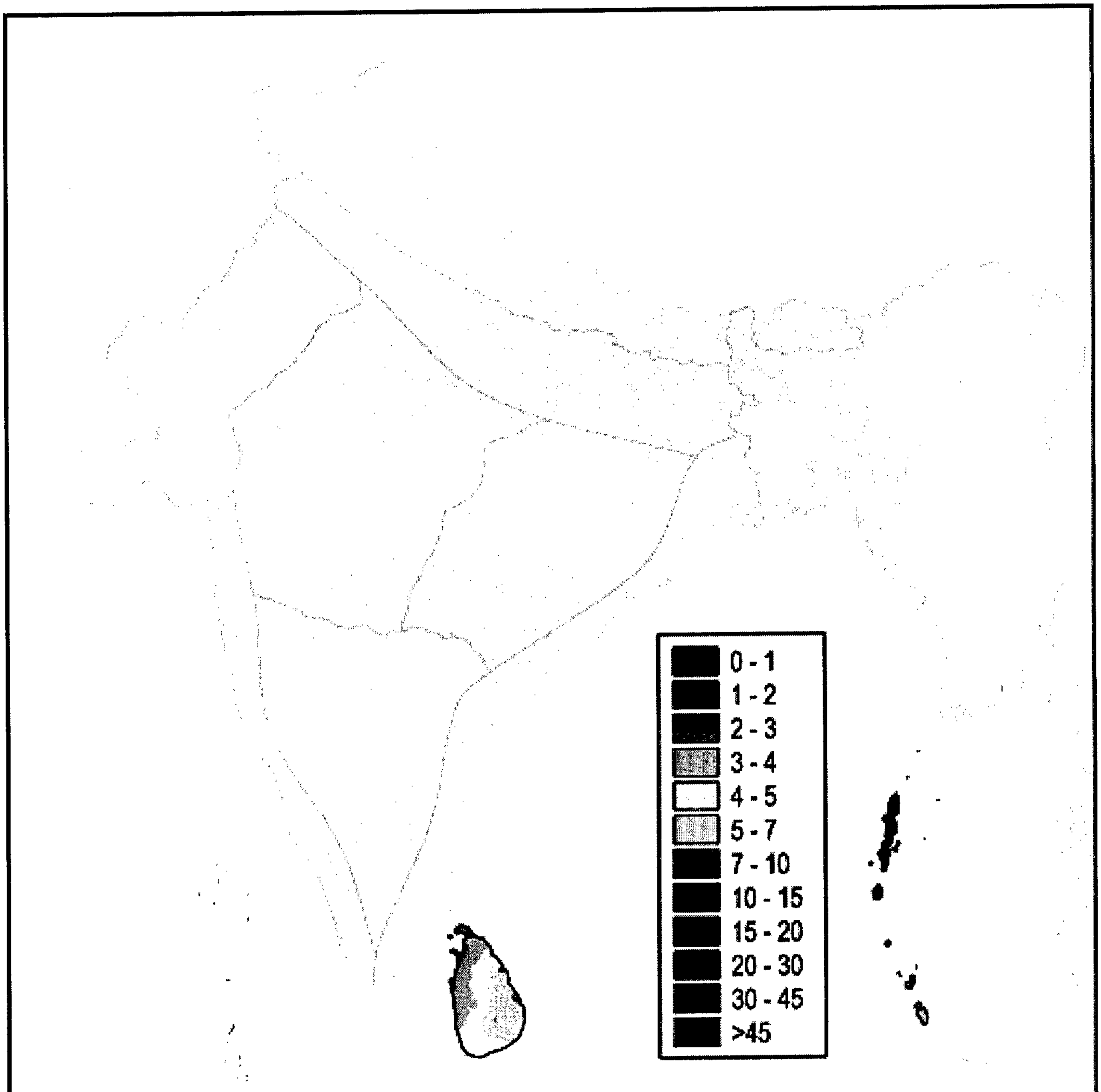


Figure 7-7. January Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

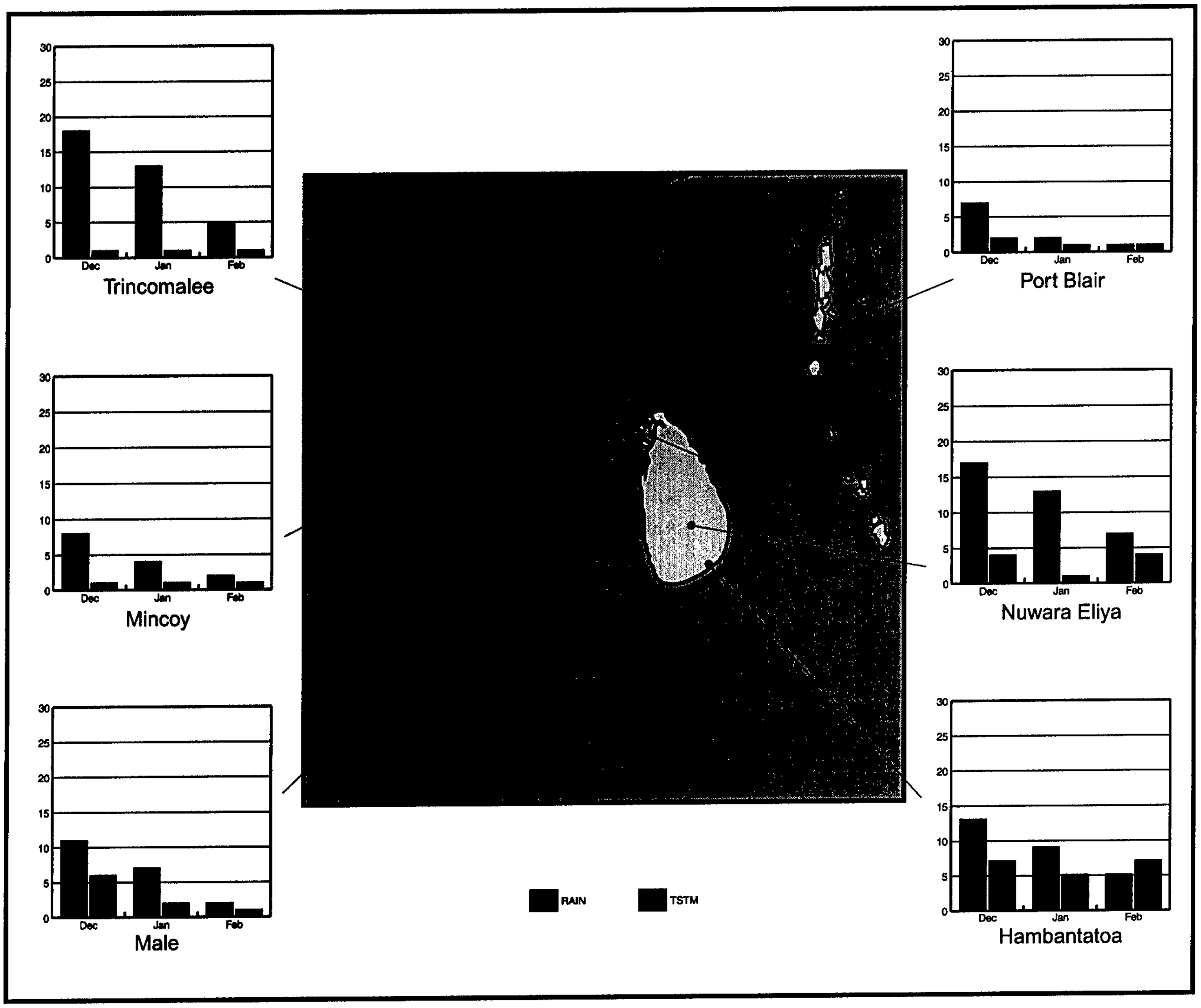


Figure 7-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Refer to Figures 7-9 and 7-10 for January mean maximum and minimum temperatures, respectively.

Sri Lanka. The mean highs in eastern Sri Lanka are 81° to 83°F (27° to 28°C). The mean lows are 77° to 79°F (25° to 26°C). In the west, high temperatures are warmer because there is less cloud cover in the lee of the central mountains. The mean highs are 85° to 88°F (29° to 31°C). Mean lows are 72° to 73°F (22° to 23°C). Extremes in the east are as high as 91°F (33°C) and as low as 67°F (19°C). In the west, extreme highs are 99° to 102°F (37° to 39°C). Extreme lows are 61° to 64°F (16° to 18°C). Because the air cools moist adiabatically with elevation, the mountains are cooler. Temperatures cool roughly 3 Fahrenheit (1.5 Celsius) degrees per 1,000 feet (300 meters). At high elevations, the mean maximum is 70°F (21°C) and mean minimum is 46°F (8°C). Temperatures rarely exceed 78°F (26°C) and may fall as low as 27°F (-3°C). Although it does not last long after sunrise, frost occasionally occurs at high elevations.

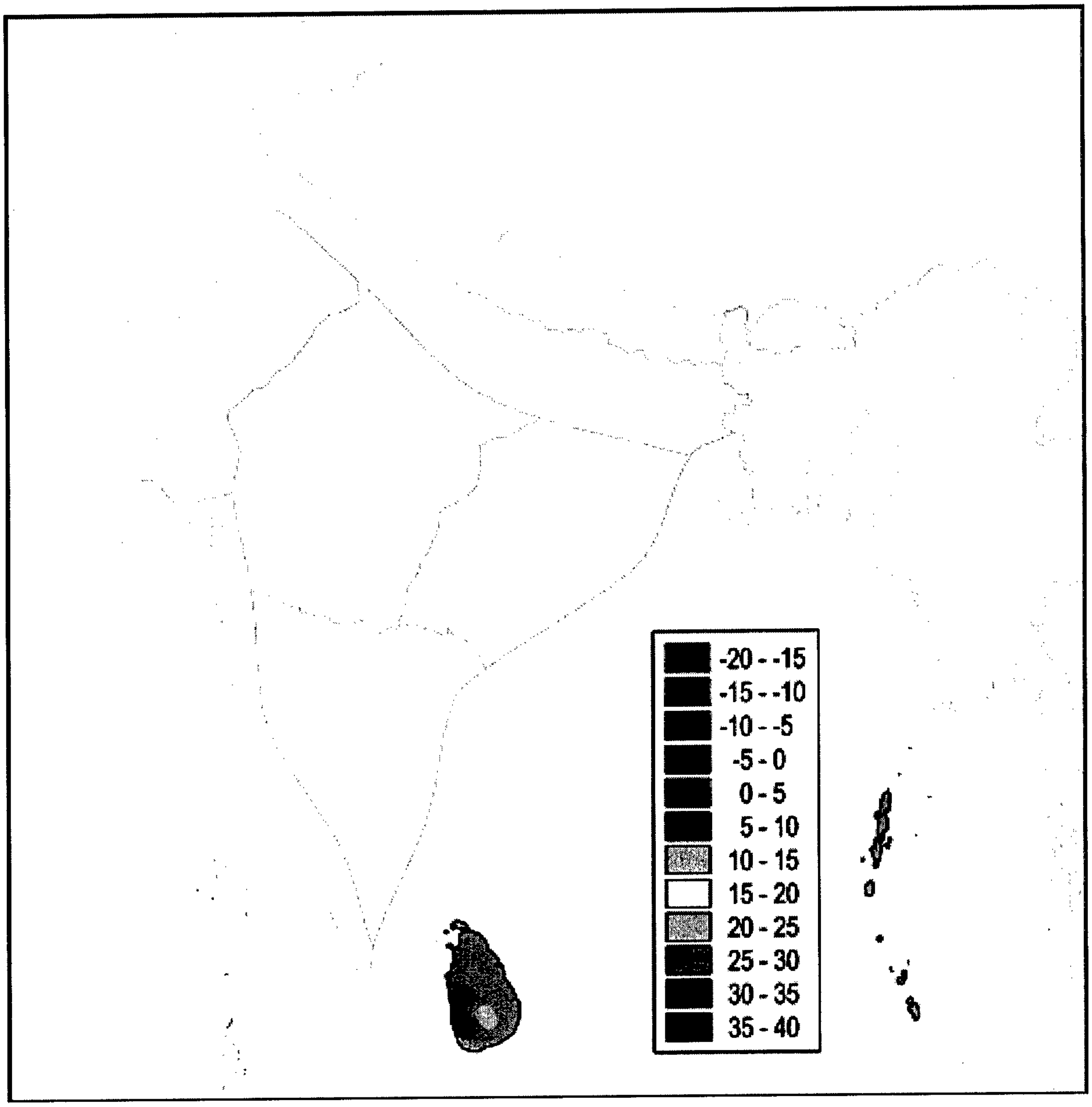


Figure 7-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures January. Daily high temperatures are often higher or lower than the mean. Mean maximum temperatures during other months may be lower, especially at the beginning and ending of the season.

Nicobars and Andamans. Mean highs are 85° to 87°F (29° to 31°C) and mean lows are 73° to 77°F (23° to 25°C). Extreme highs are 87° to 90°F (31° to 33°C) and extreme lows are 63° to 69°F (17° to 21°C) in the Lakshadweeps only. The temperature does not fall below 72°F (22°C) in the Maldives.

Lakshadweeps and Maldives. Mean highs are 85° to 87°F (29° to 31°C) and mean lows are 74° to 76°F (23° to 24°C). Extreme highs are 91° to 94°F (33° to 34°C) and extreme lows are 66° to 68°F (19° to 20°C) only in the Lakshadweeps. Temperatures do not fall below 73°F (23°C) in the Maldives.

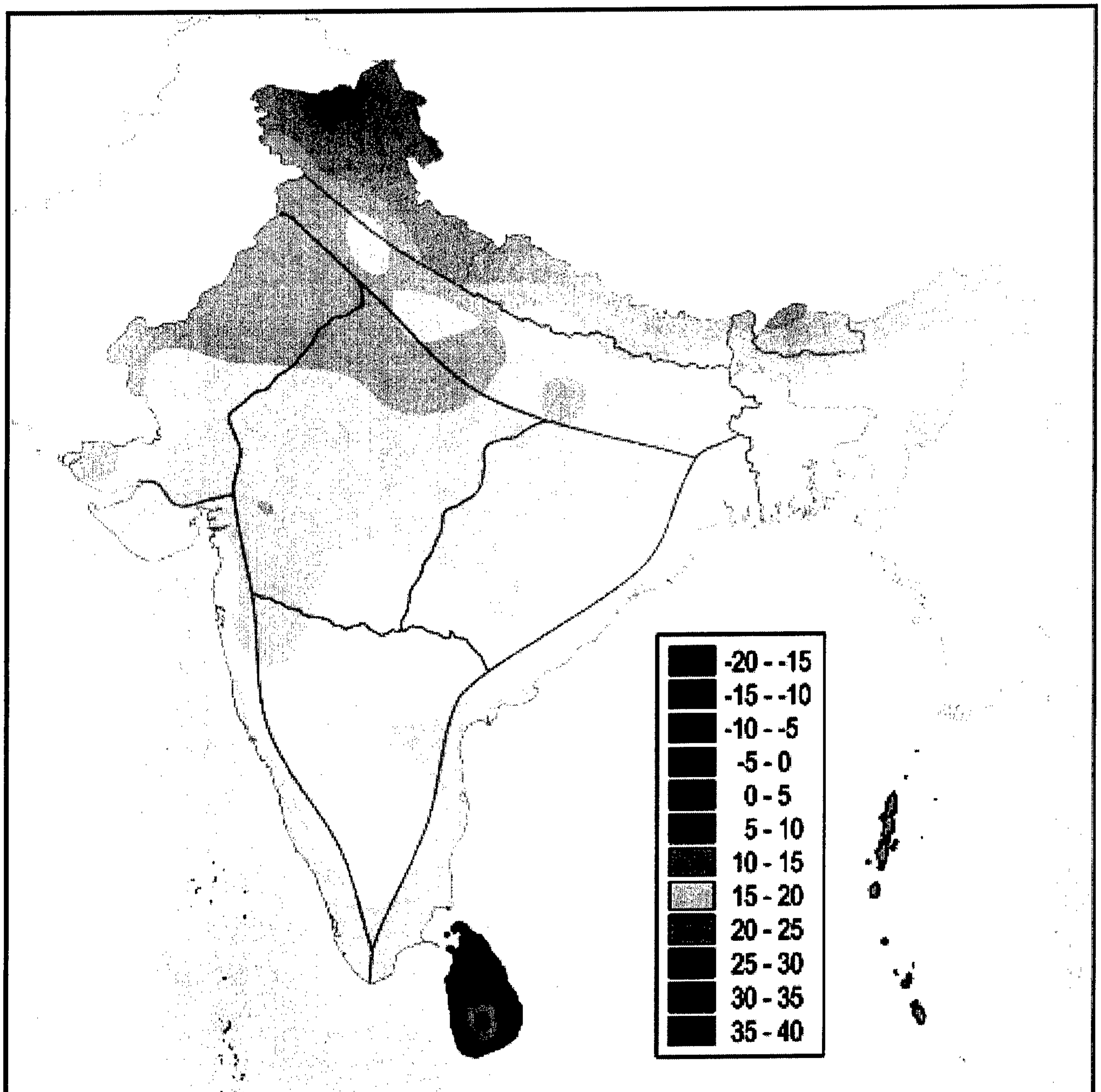


Figure 7-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for the month. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other winter months may be higher, especially at the beginning and ending of the season.

Hot Season

General Weather. This is when the dry weather reaches its peak. Islands do not get as hot as the mainland, but temperatures rise under skies that are often clear or scattered. The thermal high over Asia is seriously weakened by March. The thermal low over Australia disappears, and the equatorial trough (ET) heads north with the sun. Wind circulation is confused. In the Maldives, the most violent storms of the year occur with the ET in this season, especially in April. They bring heavy precipitation, strong winds, and high seas. The Maldives come under the influence of the southwest monsoon early. A brief transition period ends by the end of March. The ET moves north of them in April and their rainy season begins. The ET crosses over Sri Lanka in May. The northward travel of the ET is not a smooth, steady one. It oscillates north and south, moves many miles in surges then retreats, and stagnates in one place for days at a time. In this transition season, "onset vortices" travel along the ET at the leading (northern) edge of the southwest monsoon air mass. These vortices produce rain, rainshowers, and thunderstorms and signal the "monsoon burst" of the changing season. The hottest weather of the year ends with this transition. Although not common, tropical cyclones do develop in the Bay of Bengal in the hot season. Their mean track brings them ashore on the northeastern coast of India most but the southern track occasionally takes them over Sri Lanka. Quite a bit of their power is stripped off as they pass over the Indian peninsula, and the Lakshadweeps have less heavy weather from them as a result. Tropical cyclones are more likely to occur in May, with the ET as it shifts north, than in April or March.

Sky Cover. Figure 7-11 shows the seasonal percent frequency of ceilings less than 5,000 feet for selected South Asian Islands locations.

Sri Lanka. The Central Highland is the cloudiest place on the island; the position of the cloudiness depends on the prevailing wind. At Nuwara Eliya, March ceilings below 5,000 feet occur 10-20 percent overnight, 30 percent of the time from mid-morning to mid-afternoon, and 45 percent of the time from late afternoon to mid-evening. In April and May, late afternoon ceilings below 5,000 feet occur 55-65 percent of the time. April rates for the rest of the day are about the same as in March, but May ceilings occur 30 percent of the time overnight through sunrise and 45-55 percent of the time from mid-morning to mid-afternoon. Elsewhere, ceilings and cloud cover increase from March to May in the western areas as the ET moves north. At the same time, the eastern areas become less cloudy. In the west, March ceilings below 5,000 feet occur 5-15 percent of the time most of the day and 20-30 percent of the time in the afternoon hours. In April and May, most of the day has ceilings below 5,000 feet 15-25 percent of the time in the west and afternoon maximum rates of 40-50 percent of the time. The rates in May are at the high end and the April rates are at the low end of the ranges. On the east side of the island, March through May ceilings below 5,000 feet occur 5-10 percent of the time with a maximum of 10-15 percent of the time in the afternoons. For the whole island, except for the highlands, ceilings below 1,000 feet occur only with convective precipitation, and usually last under 1 hour.

Nicobars and Andamans. Ceilings below 5,000 feet occur most in the afternoons and in May. In March, afternoon ceilings below 5,000 feet occur 10-15 percent of the time. In April, they occur 30-40 percent of the time, and in May, they occur 45-55 percent of the time. The rest of the day, March and April have ceilings below 5,000 feet 10-15 percent of the time, but May has them 25-35 percent of the time. Ceilings below 1,000 feet occur roughly 5 percent of the time in May only, usually in association with precipitation.

Lakshadweeps and Maldives. Mean cloudiness rises from scattered to broken from March to May, but most cloud cover tends to be above 5,000 feet over these low islands. Ceilings below 5,000 feet occur less than 5 percent of the time in March and April and 10-15 percent of the time in May. The maximum rate is in the afternoons. Ceilings below 1,000 feet do not occur outside of convective precipitation.

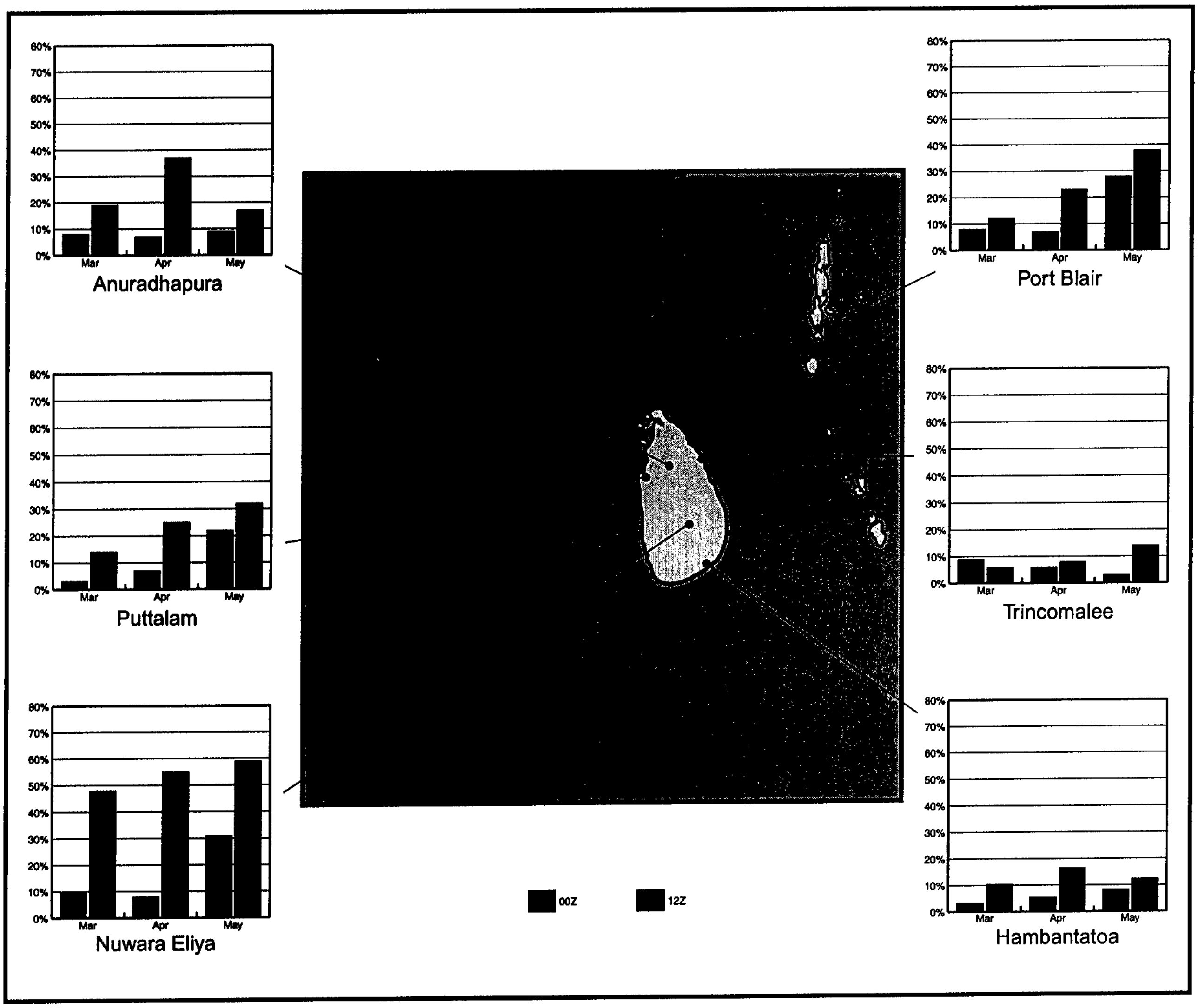


Figure 7-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Figure 7-12 shows the seasonal percent frequency of visibility below 21/2 miles (4,000 meters) for represrentative South Asian Islands locations.

Sri Lanka. Visibility is good in most of Sri Lanka. It is seldom less than 4,000 meters except during afternoon rainshowers. At Puttalam, late afternoon rainshowers lower visibility 17 percent of the time in March and 29 percent of the time in April and May. Conditions improve within 1-2 hours. Other locations rarely report visibility less than 4,000 meters. At high elevations, visibility is poorest in the afternoon when moisture lifts in daytime heating. At Nuwara Eliya, visibility in the afternoons through evenings is below 4,000 meters 10-20 percent of the time, most often in May. The rest of the day, it occurs 5 percent or less.

Nicobars and Andamans. At Port Blair, visibility is below 4,000 meters only during May. It is below 4,000 meters 10 percent of the time in the mornings and 15 percent of the time in the afternoons. The rest of the day, visibility remains good. Restricted visibility is not common in most of the area. It occurs only with precipitation. The exception is on cloud-cloaked slopes at higher elevations in the Andamans. There, visibility will be poorest during the afternoon hours when low level moisture lifts in daytime heating.

Lakshadweeps and Maldives. Visibility remains good outside of precipitation.

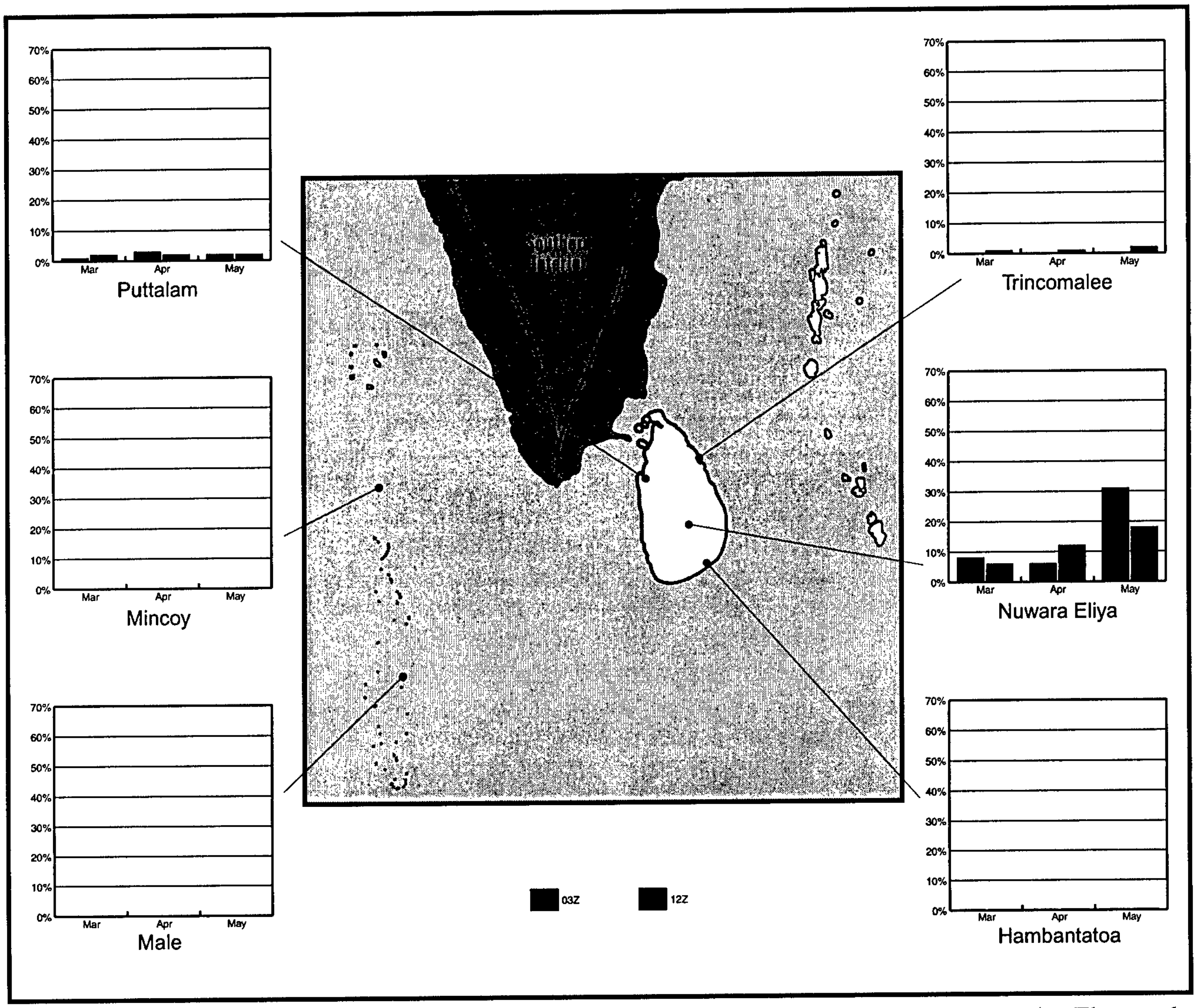


Figure 7-12. Hot Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Figure 7-13 depicts surface wind roses in April for selected South Asian Islands locations.

Sri Lanka. Surface winds are variable during March but occur most frequently from the southeast-southwest. By the mid-April, winds are from the southwest. Speeds are generally 7-10 knots, except on the south coast at Hambantatoa where winds are usually 8-15 knots with occasional gusts as high as 30 knots. Sea breeze winds are augmented by the beginning southwest monsoon flow on the west coast. Night calms occur 45-60 percent of the time in the southern two-thirds of the coast but only 20-30 percent of the time on the northern third. During the day, calms occur roughly 10 percent of the time all along the coast. The monsoon flow is still very shallow during the transition season. It does not cross the interior mountains and bring southwest winds to the east coast until the monsoon is in full swing. On the east coast, local wind systems prevail. Overnight, a land breeze at 5 knots or less occurs. During the day, a sea breeze flows from northeast to southeast at 10-15 knots. Calms rarely occur during the day. In the mountainous interior, winds are dictated by terrain. At Nuwara Eliya, winds flow from the east at 5-10 knots at all hours because mountain ranges northeast and southwest of the station deflect the winds to an easterly direction. Calms occur 70 percent of the time at night and 30 percent of the time during the day.

Nicobars and Andamans. Night winds are variable at 5 knots or less, with a high rate of calms throughout the area. Calms occur 85-100 percent of the time at night and 75-90 percent of the time during the day. When the winds blow during the day, they generally come from the northeast at 5-10 knots into early May. When the ET passes, the winds shift abruptly to come from the southwest, and speeds increase to 10-15 knots with gusts to 25 knots. Until the ET passes, winds vary from one end of the chain of islands to the other. By the end of May, the transition is complete for the whole area.

Lakshadweeps and Maldives. Night winds for the whole area come from the northwest at 10-15 knots. Gusts range up to 25 knots except for Gan, at the southern end of the Maldives, where winds can rise to 15-20 knots with gusts to 30 knots or higher. Gan night winds come from the southwest to the northwest then steady to come from the west during the day. During the day, the winds in the Lakshadweeps remain from the northwest at 10-15 knots with gusts to 25 knots. In the Maldives, winds come more from the west to west-northwest at 12-20 knots with gusts of 30-35 knots. Calms occur roughly 15-20 percent of the time at night throughout the area and 5 percent of the tine during the day.

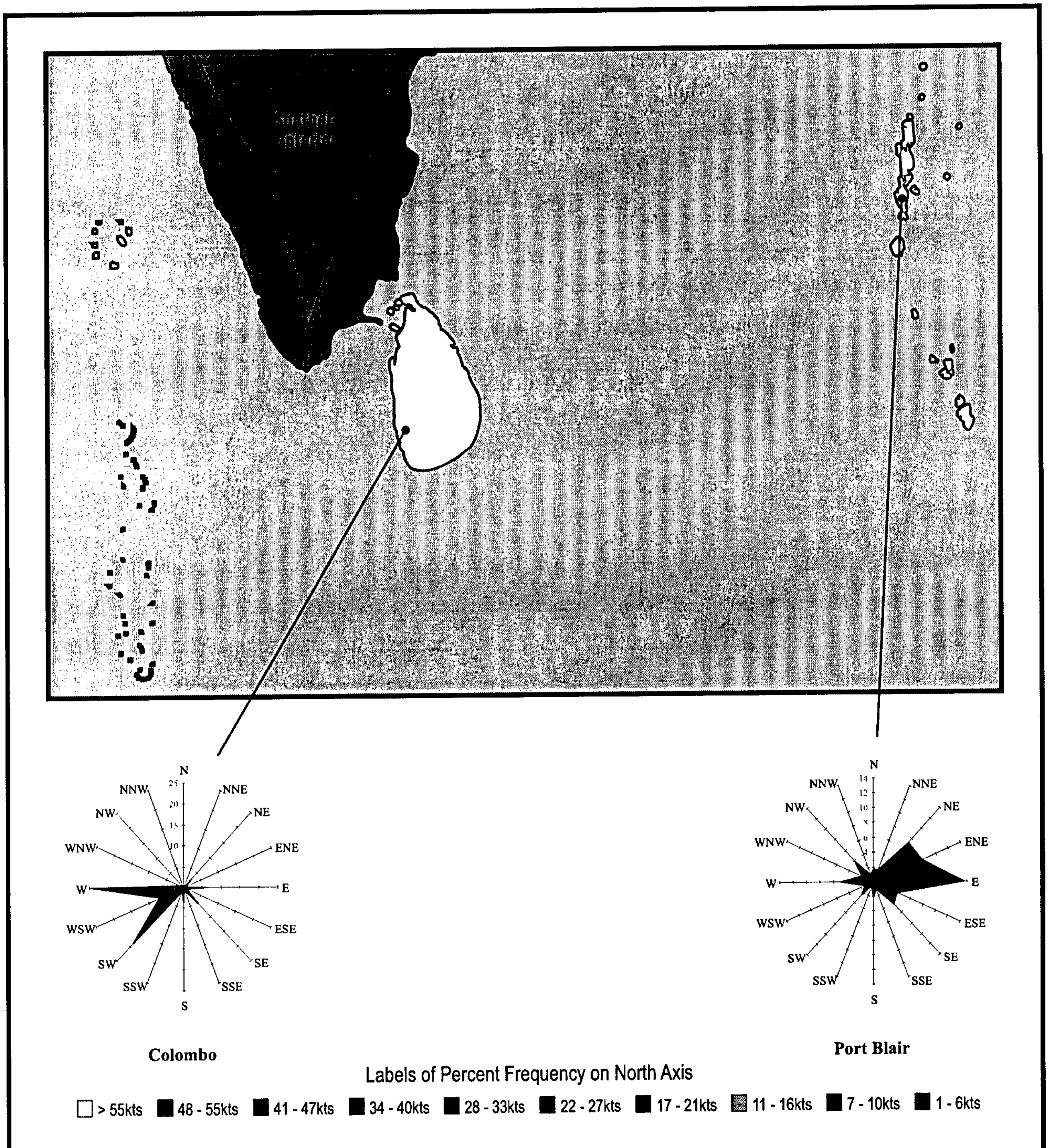


Figure 7-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Upper-air winds are from the northeast or east except at the 5,000-foot level. Here, the winds are quite variable at 16-30 knots. The strongest winds at 5,000 are from a westerly direction. At 10,000 feet the winds are northeast at 21-40 knots. Winds are easterly at 26-50 knots at 18,000 feet. Winds at 30,000 are somewhat variable, but east winds predominate at speeds of 31-60 knots. Figure 7-14 is a composite using Colombo, Port Blair and Gan and shows the typical April upper-air winds across the South Asian Islands.

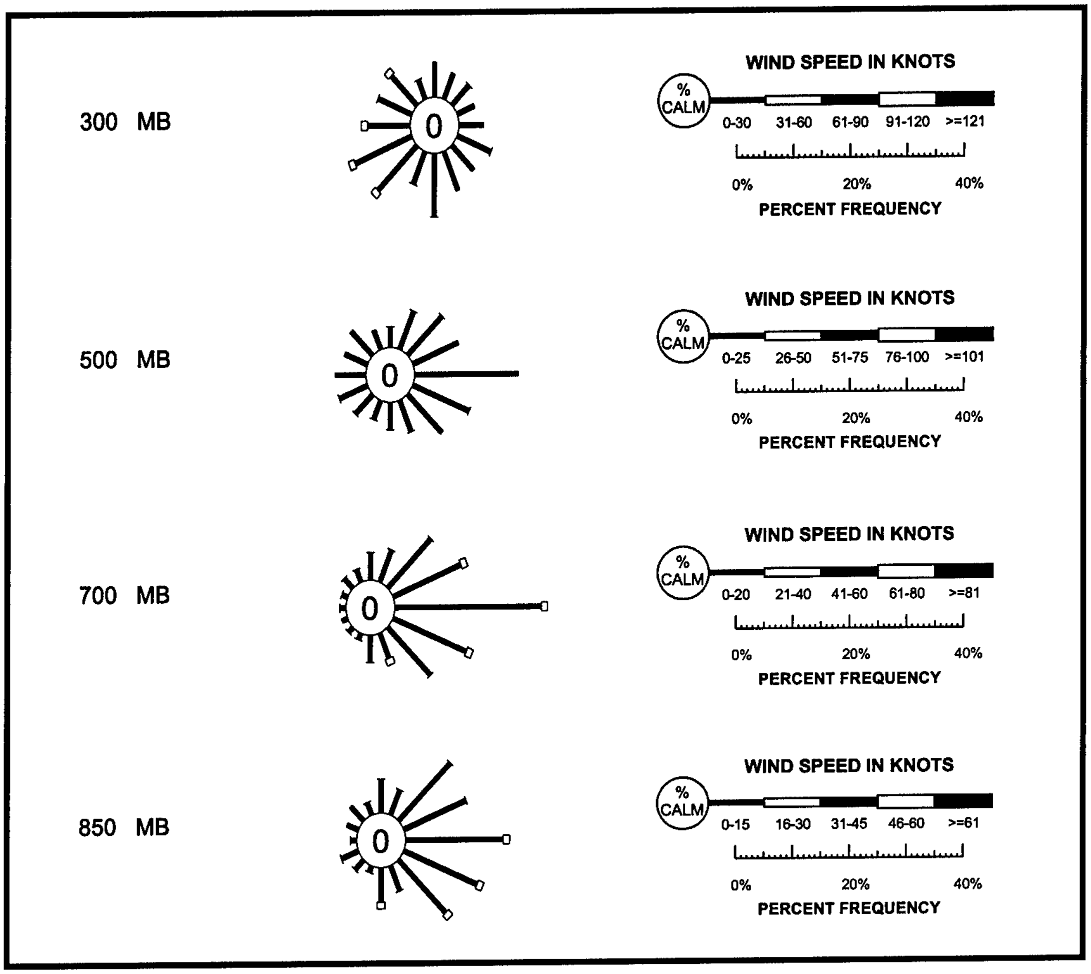


Figure 7-14. April Upper-Air Wind Roses. The composite (Colombo, Port Blair and Gan) wind roses depict wind speed and direction for standard pressure surfaces between 850 mb and 300 mb in the South Asian Islands.

Precipitation. Figure 7-15 depicts April mean precipitation amounts for the South Asian Islands, and Figure 7-16 shows seasonal precipitation and thunderstorm days.

Sri Lanka. The southwest monsoon moves across Sri Lanka in this season. In March, leeward sites receive 1-3 inches (25-76 mm) of rain over 2-7 days, and windward sites get 3-6 inches (76-152 mm) over 10-16 days. Places at higher elevations get the most rain. In April and May, leeward sites get 2-7 inches (51-178 mm) over 6-10 days. Windward sites receive 8-12 inches (203-305 mm) in April and May over 11-16 days in April and 18-24 days in May, respectively. On some windward mountain slopes, 19-22 inches (483-559 mm) of rain occur in May. Thunderstorms occur far more on the windward sides of the island than the leeward. In March, they occur 3-7 days on the eastern side and leeward highland locations and 10-14 days on the west side and windward highland sites. April is the peak activity month with 14-18 thunderstorms days in windward sites and 8-10 days in leeward sites. In May, windward sites get 10-15 thunderstorm days and leeward sites get 5-8. Although station reports do not show it, thunderstorm activity is frequent over the whole island. Thunderstorms tend to occur most in the afternoon hours. Lightning is often observed in the distance, which means thunderstorm activity is greater than that shown in station reports. The inter-monsoonal periods are when thunderstorms are most frequent. Soft hail is occasionally associated with the most violent storms, especially in April. In the Central Highland, there are almost always thunderstorms in progress somewhere.

Nicobars and Andamans. March is a relatively dry month in this area, then rain amounts rise as the ET approaches. The Nicobars have slightly more rain than the Andamans in March, an average of 1-1.5 inch (25-38 mm) as opposed to 0.5 inch (13 mm). By April, the amounts begin to even out as the higher terrain of the Andamans begins to cause orographic convection. In April, the average in the area is 2.5-3.5 inches (64-89 mm). May amounts rise to southwest monsoon amounts, 13-16 inches (330-406 mm). Rain falls on 3-5 days in March and 4-6 days in April. In May, rain days jump sharply to 11-18 days with more in the Nicobars than in the Andamans. Thunderstorms occur 3-5 days in March and 4-8 days in April and May. Port Blair, on South Andaman, reports more thunderstorm days than rain days in April as convection develops over the nearby mountains.

Lakshadweeps and Maldives. In the Lakshadweeps and the northern Maldives, rain falls 2-4 days in March, 4-6 days in April, and 10-14 days in May. Amounts also increase over the season. In March, the Lakshadweeps get an average of 0.5-1 inch (13-25 mm) over 2-3 days , and the northern Maldives receive 3-4 inches (76-102 mm) over 4-6 days. The southern Maldives get more rain, an average of 4-6 inches (102-152 mm) over 8-10 days in March. The transition from the northeast to the southwest monsoon is very brief in the Maldives. The southwest monsoon moves over the northern Maldives as early as the beginning of April, often with violent storms. In April, the Maldives average 3-5 inches (76-127 mm) over 6-8 days, and the Lakshadweeps average 2-2.5 inches (51-64 mm) over 3-5 days. By May, the whole area is under the southwest monsoon and averages 6-8 inches (152-203 mm) of rain over 12-15 days.

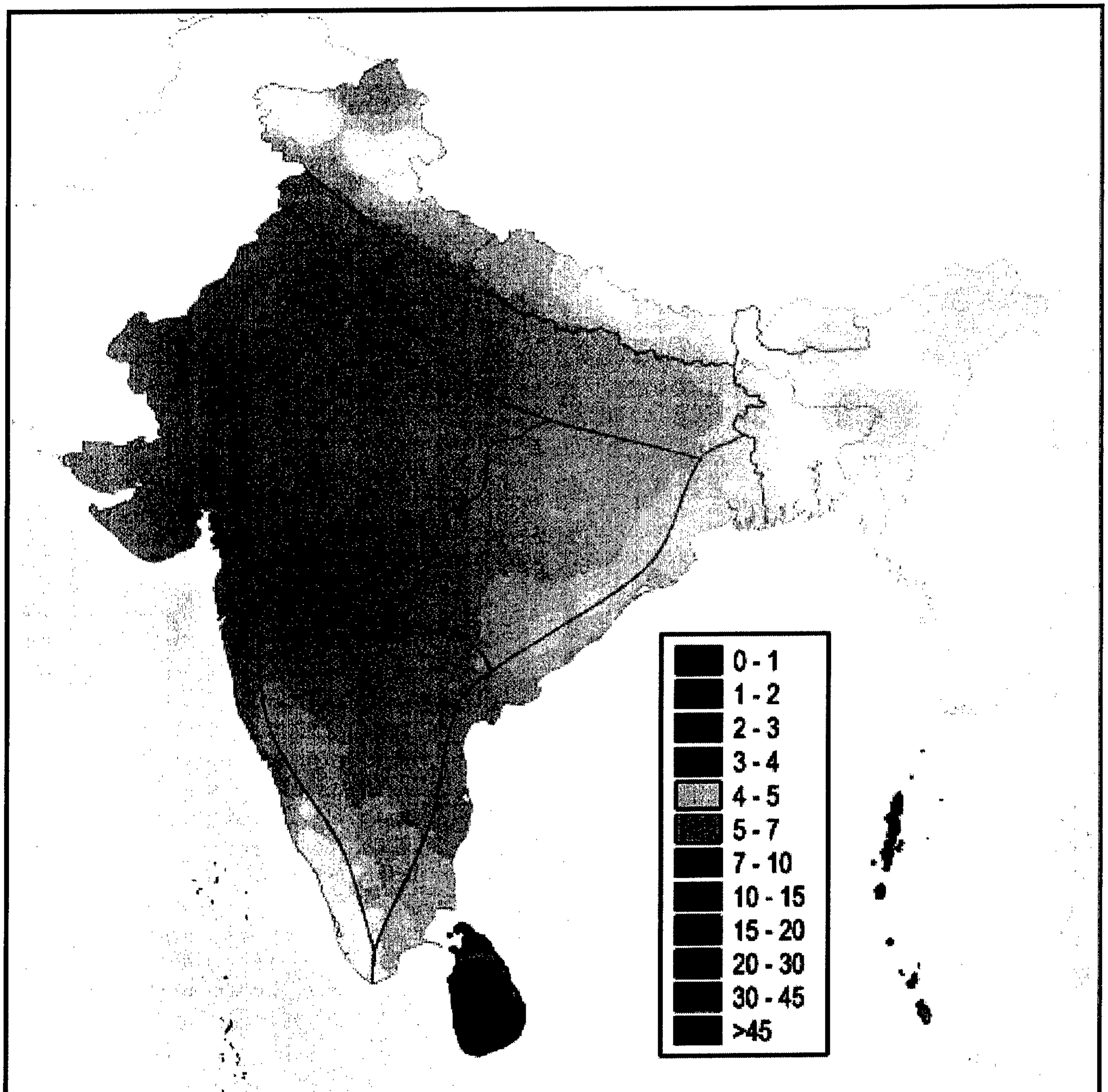


Figure 7-15. April Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

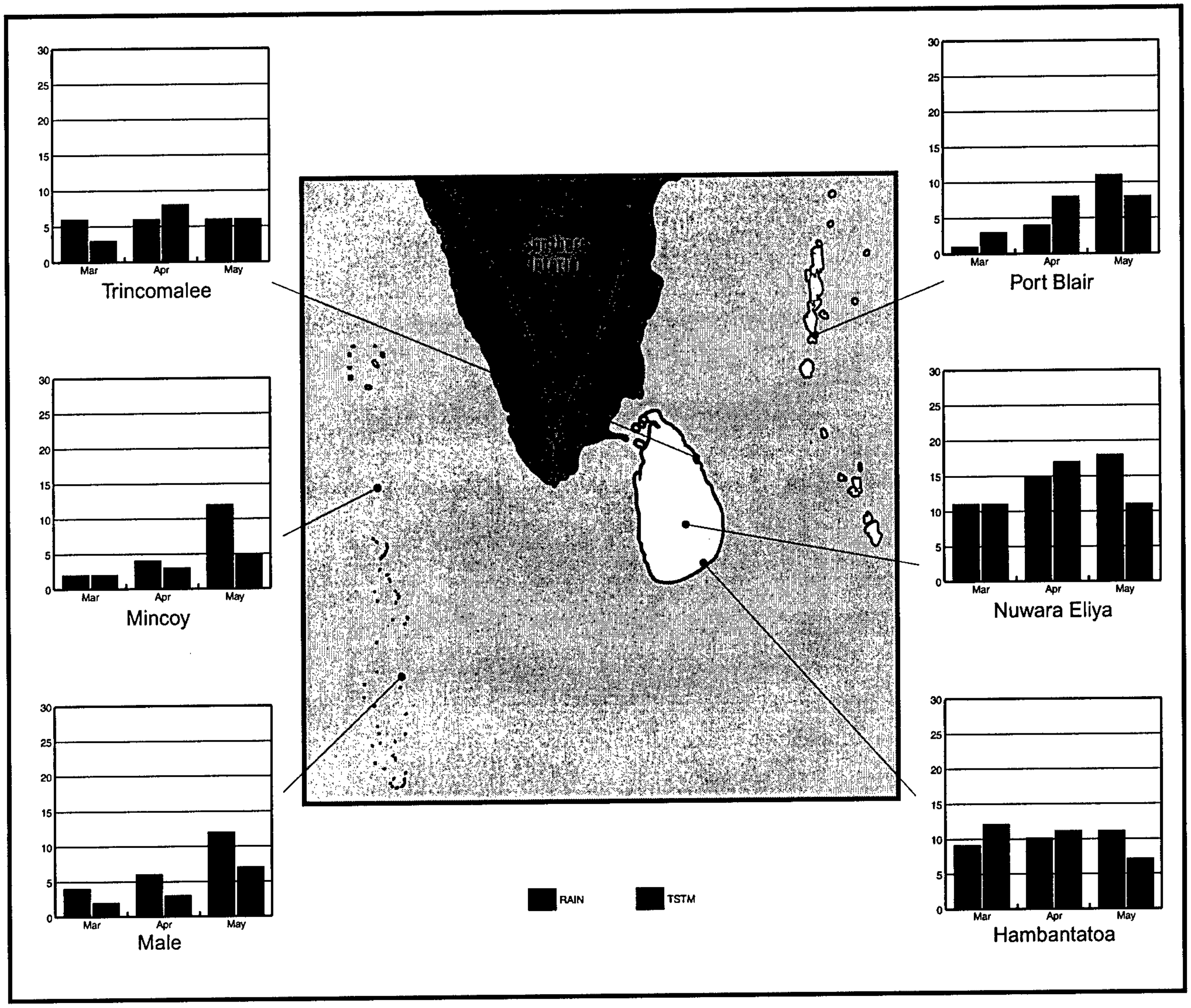


Figure 7-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Refer to Figures 7-17 and 7-18 for April mean maximum and minimum temperatures, respectively.

Sri Lanka. Temperatures are warmer, and diurnal ranges are small. Mean highs are 85° to 90°F (29° to 32°C). Mean lows are 75° to 81°F (24° to 27°C). The extreme highs are 96° to 102°F (36° to 39C), slightly cooler in the east than in the west. This is the warmest time of year in the west. Because of moist adiabatic cooling with elevation, the mean high at high elevations in the mountains is 72°F (22°C), and the mean lows are 46° to 49°F (8° to 9°C). The extreme high is 79°F (26°C). At Nuwara Eliya, an extreme low of 29°F (-2°C) was reported in March. Although it does not last long after sunrise, frost occasionally occurs at high elevations. The rate of adiabatic cooling is roughly 3 Fahrenheit (1.5 Celsius) degrees per 1,000 feet (300 meters).

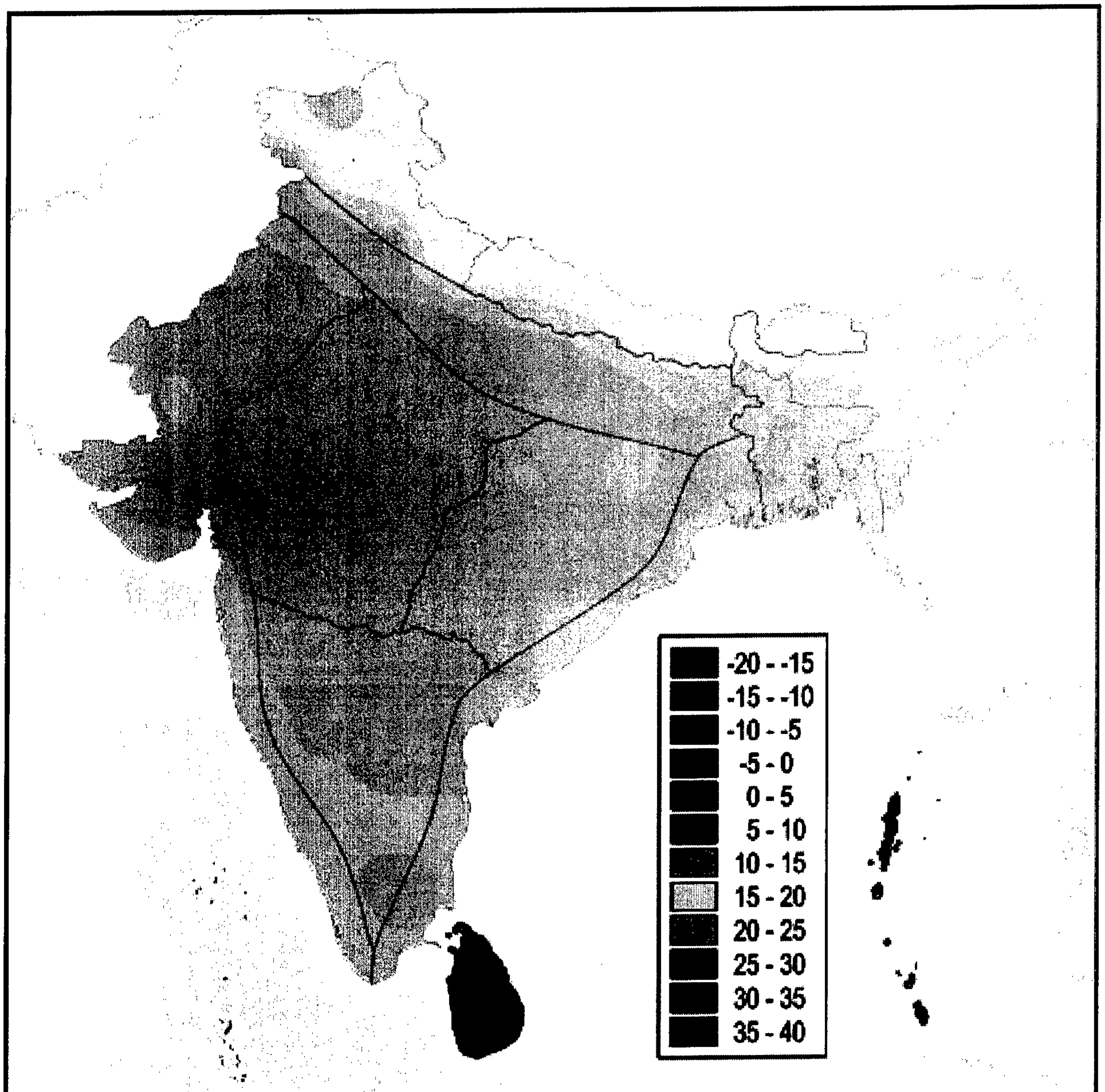


Figure 7-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher or lower than the mean. Mean maximum temperatures during other months may be lower or higher, especially at the beginning and ending of the season.

Nicobars and Andamans. The mean highs in the whole area average 87° to 90°F (31° to 32°C) and the mean lows are 72° to 77°F (22° to 25°C). Extreme highs are 95° to 99°F (35° to 38°C) and extreme lows are 64° to 71°F (18° to 22°C). Temperatures cool adiabatically roughly 3 Fahrenheit (1.5 Celsius) degrees per 1,000 feet (300 meters) rise in elevation. This is more significant in the Andamans than the Nicobars.

Lakshadweeps and Maldives. The mean high temperatures are 86° to 88°F (30° to 31°C) and the mean lows are 77° to 80°F (25° to 27°C). Extreme highs in the Lakshadweeps are 95° to 99°F (35° to 38°C) and extreme lows are 69° to 71°F (21° to 22°C). In the Maldives, extreme highs are cooler, 92° to 95°F (33° to 35°C), and the extreme lows are warmer, 74° to 76°F (23° to 24°C).

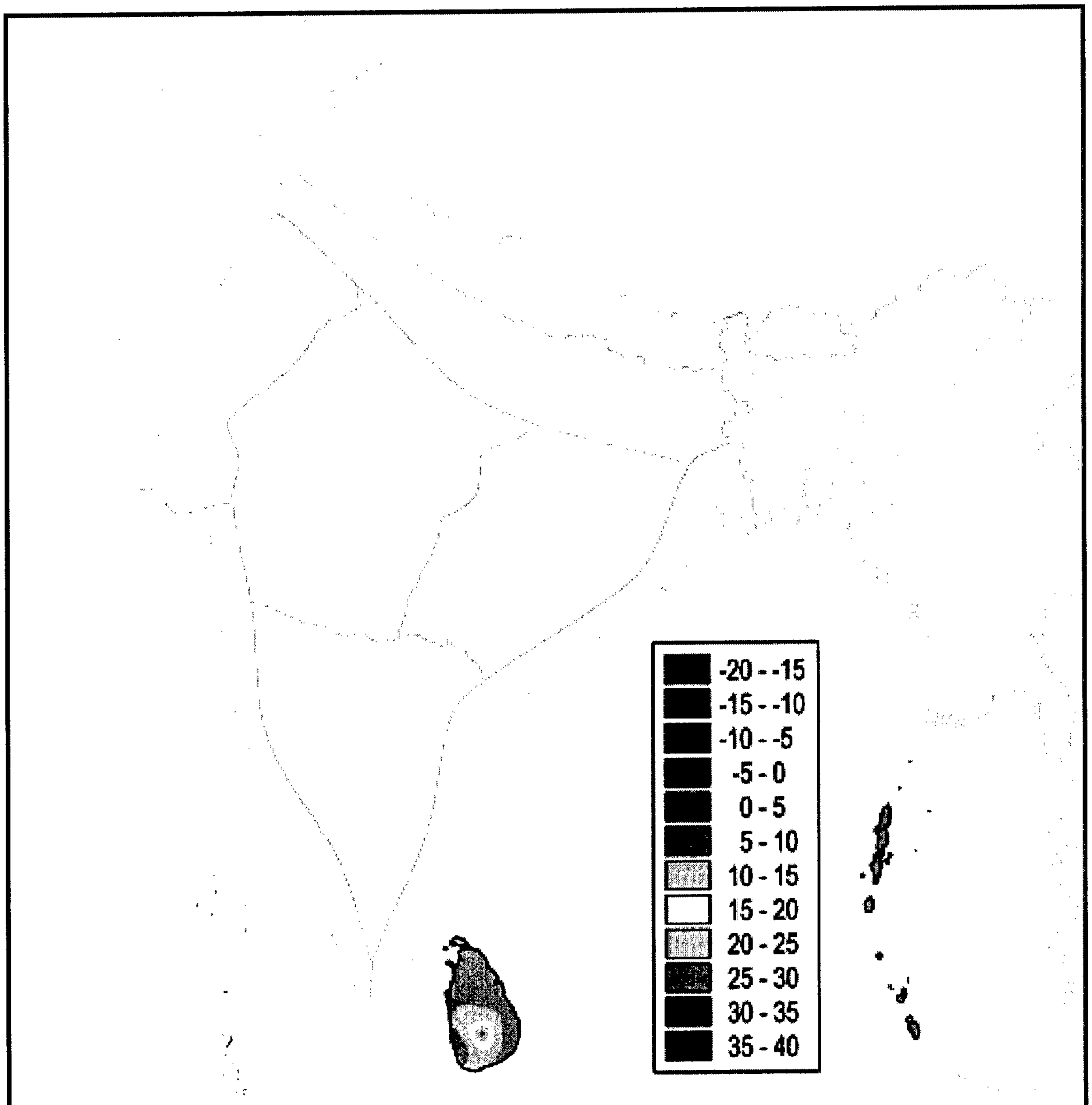


Figure 7-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Daily low temperatures are often higher or lower than the mean. Mean minimum temperatures during other months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. The whole region is fully engulfed by the moist flow of the southwest monsoon. Although generally thought to begin in June, the monsoon actually begins as early as April in the Maldives. The rest of the region gets the southwest monsoon in stages from south to north. By the end of May, the whole region is firmly under southwest monsoon flow. Easterly flow aloft extends almost to the foot of the Himalayas. The India-Myanmar trough sets up in this season. This southwest-northeast oriented trough develops over the Bay of Bengal and is a prime breeding ground for monsoon depressions. Easterly waves and other tropical disturbances are enhanced when they make their way into this convergence zone and sometimes develop into full-blown tropical cyclones. Of all the islands in the region, Sri Lanka is the most likely to experience severe weather and heavy rain with these storms. The Andaman and Nicobar islands are too far east and the Lakshadweep islands are somewhat protected by the Indian peninsula. The Maldives are too far south to get much more than the perimeter rains and clouds of passing storms as they move west. Mean tropical cyclone tracks are generally in the northern Bay of Bengal. However, a few storms still take the southern track across Sri Lanka. In June and July, most storms tend to make landfall in the northeastern corner of the bay. In August through October, the tracks shift south slightly.

The equatorial westerlies are a hallmark of the southwest monsoon. Created by deflected outflow of the South Indian Ocean high, these low-level winds spread out over the north Indian Ocean. As these winds begin to flow, the Somali jet develops. This low-level jet transports Southern Hemispheric air across the equator. This unstable, warm, moisture-laden air is what makes the southwest monsoon season rainy. The tropical easterly jet (TEJ), a southwest monsoon feature, provides an upper-level exhaust for Bay of Bengal convection. The bay is a prime zone for the development of tropical cyclones, monsoon depressions, and other cyclonic storms. Fortunately, storms in the Bay of Bengal are so confined in the enclosed bay, they do not become as powerful as open ocean storms can. They can still carry high winds, heavy surf, and vast amounts of precipitation. Most of the precipitation in Bay of Bengal coastal areas occurs in the southwest monsoon season.

The deep, wide band of upper-air easterlies overlays the equatorial westerlies. Easterly waves ride this powerful current of air and trigger the development of monsoon depressions and tropical cyclones. By the end of the season, the band of easterlies retreats toward the equator.

Thermal lows set up over the central Indian subcontinent and over the Tibetan Plateau. The Indian low becomes part of the greater Asiatic low and trough that extends from northwestern India to the Sahara. This is a source of migratory lows that move across the subcontinent and into the Bay of Bengal. Overlying the Tibetan low is the Tibetan anticyclone, which develops between the strong, deep westerlies of the Northern Hemispheric midlatitudes and the strong, deep easterlies of the low latitudes. The stronger the thermal low, the stronger the anticyclone. The southern edge of this anticyclone is a prime area for the development of monsoon depressions and other cyclonic storms in the Bay of Bengal.

Sky Cover. Figure 7-19 shows the seasonal percent frequency of ceilings less than 5,000 feet for selected South Asian Islands locations.

Sri Lanka. Cloudiness increases as the southwest monsoon becomes well established, and reaches a maximum in September and October. The Central Highland windward slopes are the cloudiest places on the island. There, ceilings below 5,000 feet occur 60-70 percent of the time most of the day and 70-80 percent of the time in the afternoon through evening. Ceilings below 1,000 feet occur 45-55 percent of the time most of the day and 60-70 percent of the time in the afternoon through evening. Ceilings below 500 feet occur 30-40 percent of the time with the maximum rate in the afternoon through evening. Outside of the highlands, ceilings below 5,000 feet occur more on the west side of the island than on the east side. On the west side, they occur 30-40 percent of the time in June and September and 40-50 percent of the time in July and August. The maximum occurrences are in the afternoon and the minimum occurrences are around mid-evening. At that time, ceilings below 5,000 feet occur as little as 25 percent of the time all season. On the east side of the island, ceilings below 5,000 feet occur 5-15 percent of the time except on the northern plains, which are exposed to southwest monsoonal flow. There they occur 10-15 percent of the time most of the day and 40-50 percent of the time in the late morning to evening hours. Except in the highlands, ceilings below 1,000 feet occur well under 5 percent of the time everywhere, generally in heavy rain.

Nicobars and Andamans. Most of the day, ceilings below 5,000 feet occur 40-50 percent of the time. In the afternoon, they occur 50-60 percent of the time in June and September and 70-80 percent of the time in July and August. The high elevations in the Andamans will have clouds that obscure the windward mountain slopes above the LCL. Outside of elevations above the LCL, this area will have ceilings below 1,000 feet 5-10 percent of the time at all hours through the whole season, mostly in precipitation.

Lakshadweeps and Maldives. Mean cloud cover is broken through the season but commonly above 5,000 feet. Ceilings below 5,000 feet occur most in the afternoons, and most in July. Most of the day, ceilings below 5,000 feet occur 2-7 percent of the time in June and August through September. In July, they occur roughly 10 percent of the time. Late morning through early evening ceilings below 5,000 feet occur 15-20 percent of the time in July and only 10 percent of the time or less the rest of the season. Ceilings below 1,000 feet do not occur outside of heavy rain.

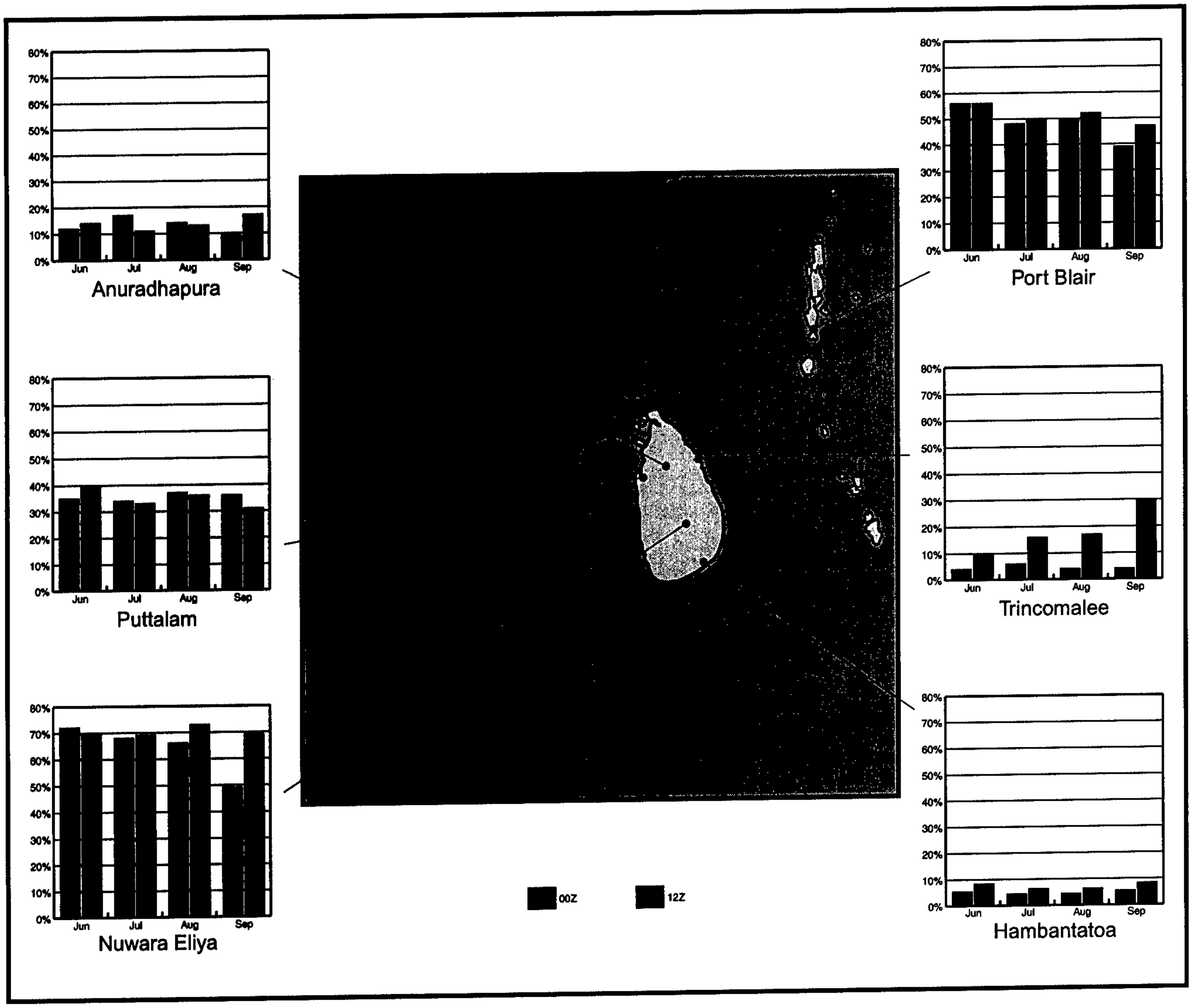


Figure 7-19. Southwest Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Figure 7-20 depicts the seasonal percent frequency of visibility below 21/2 miles (4,000 meters) for represrentative South Asian Islands locations.

Sri Lanka. Visibility is generally good everywhere on the island but the Central Highland. It is less than 4,000 meters 5 percent of the time, and rarely drops lower. During heavy downpours, the visibility will decrease sharply, but only until the storms pass. Early morning fog occurs at a few west coast locations and reduces visibility to 1 1/4 miles (2,000 meters) for short periods. The fog is shallow, and dissipates shortly after sunrise. The exception is the Central Highland. Nuwara Eliya has visibility below 4,000 meters 15-25 percent of the time at night in June through August and 60 percent of the time during the day. In September, the night conditions remain the same, but day time conditions improve--visibility below 4,000 meters occurs 40 percent of the time. This is because clouds cloak the mountain slopes above the LCL.

Nicobars and Andamans. Visibility below 4,000 meters occurs 10-15 percent of the time all season at sunrise on islands large enough to have fog. Small islands have constant winds that prevent fog. In the afternoons, visibility below 4,000 meters occurs 15-20 percent of the time, mainly in rain. The mountain slopes will be restricted in cloud above the LCL.

Lakshadweeps and Maldives. Visibility below 4,000 meters does not occur except in heavy rain.

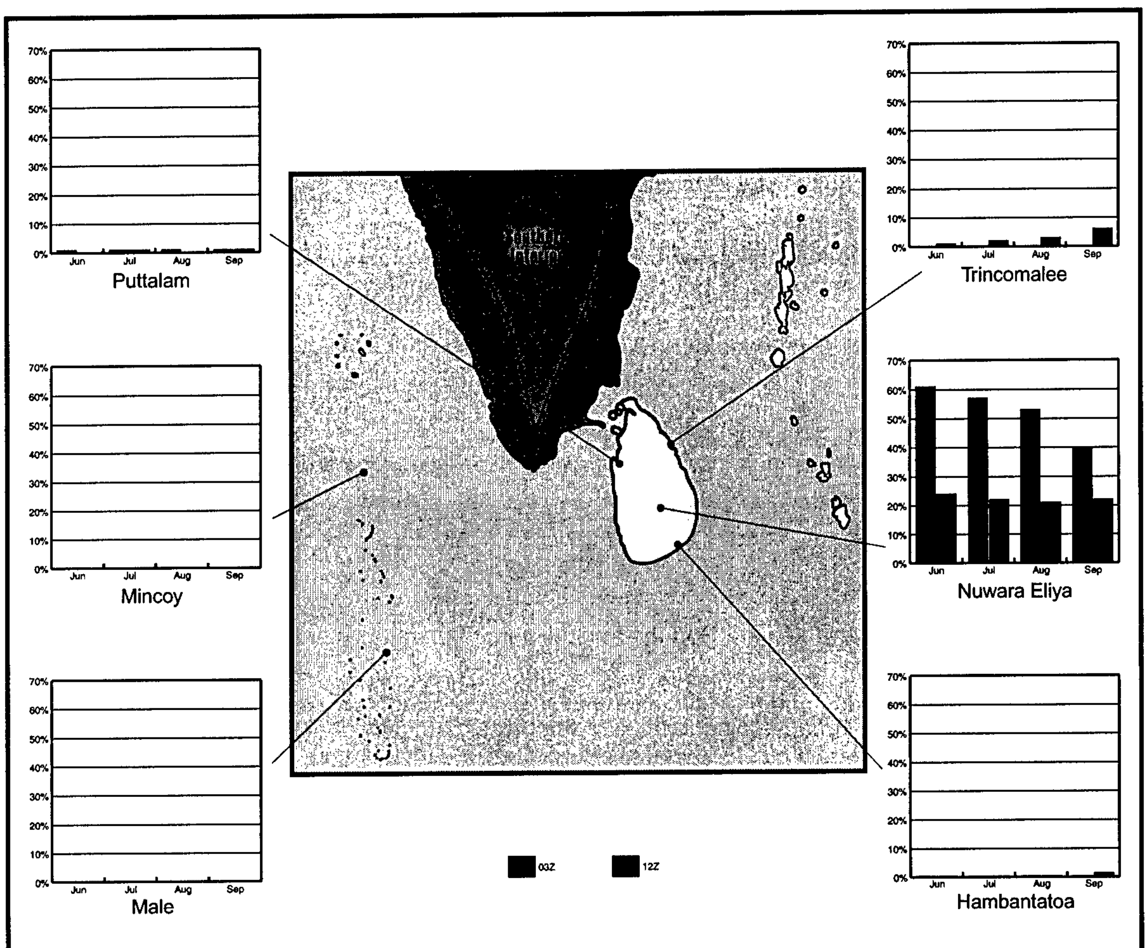


Figure 7-20. Southwest Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Figure 7-21 shows July surface wind roses for representative South Asian Islands locations.

Sri Lanka. Winds are from the southwest at 8-12 knots throughout the island. On the west and south coasts, afternoon sea breezes are augmented by the monsoon flow and gusts often reach 25 knots. Hambantatoa, on the south coast, has higher winds; steady winds are often 20-25 knots and gusts exceed 30 knots. On the west and south coasts, calms occur 5-15 percent of the time at night but rarely occur during the day. On the east coast, calms in the lee of the Central Highland occur 45-55 percent of the time at night and 5 percent of the time or less during the day. Away from the lee side areas, the north end of the east coast has a low rate of calms, under 5 percent of the time even at night. At Batticaloa, on the east coast, winds are mainly southwest, but since the station is somewhat sheltered by the central mountains, the wind direction is often driven by diurnal heating and cooling. Afternoon sea breezes will cause the winds to shift to a southeasterly direction when surface heating is intense. In the central mountains, winds at Nuwara Eliya are from the northwest. This is because the high mountain ridges direct the winds through the valley from the northwest during the season. The area east of the central mountains to the coast are subject to foehn winds, locally known as the "Batticaloa kachchan." The wind flows down the eastern slopes of the central mountains and travels to the coast. The foehn will at times override the afternoon sea breeze, and bring westerly winds to Batticaloa.

Nicobars and Andamans. The winds are from the southwest throughout this area. Daytime wind speeds range from 5-10 knots at the south end of the Nicobars and the north end of the Andamans to 10-15 knots with gusts to 25 knots from South Andaman to Car Nicobar. At both ends, calms occur 90-100 percent of the time at night and 55-65 percent of the time during the day. At Port Blair, on South Andaman, night calms occur 25-30 percent of the time and day calms occur 10 percent of the time. In the rest of the chain, night calms occur 5 percent of the time or less and day calms occur 10-15 percent of the time.

Lakshadweeps and Maldives. Winds are generally from the west or southwest at 10-15 knots with gusts to 25 knots in the Lakshadweeps. Gusts occasionally top 30 knots. Calms are rare even at night. In the Maldives, winds in the northern islands vary from the southwest to the west-northwest, with the overall direction from the west. Speeds are 15-20 knots with gusts over 30 knots. On the southern islands, winds come from the southeast to southwest, with the prevailing direction from the south. Speeds are lower, an average of 5-10 knots with occasional gusts to 20-25 knots.

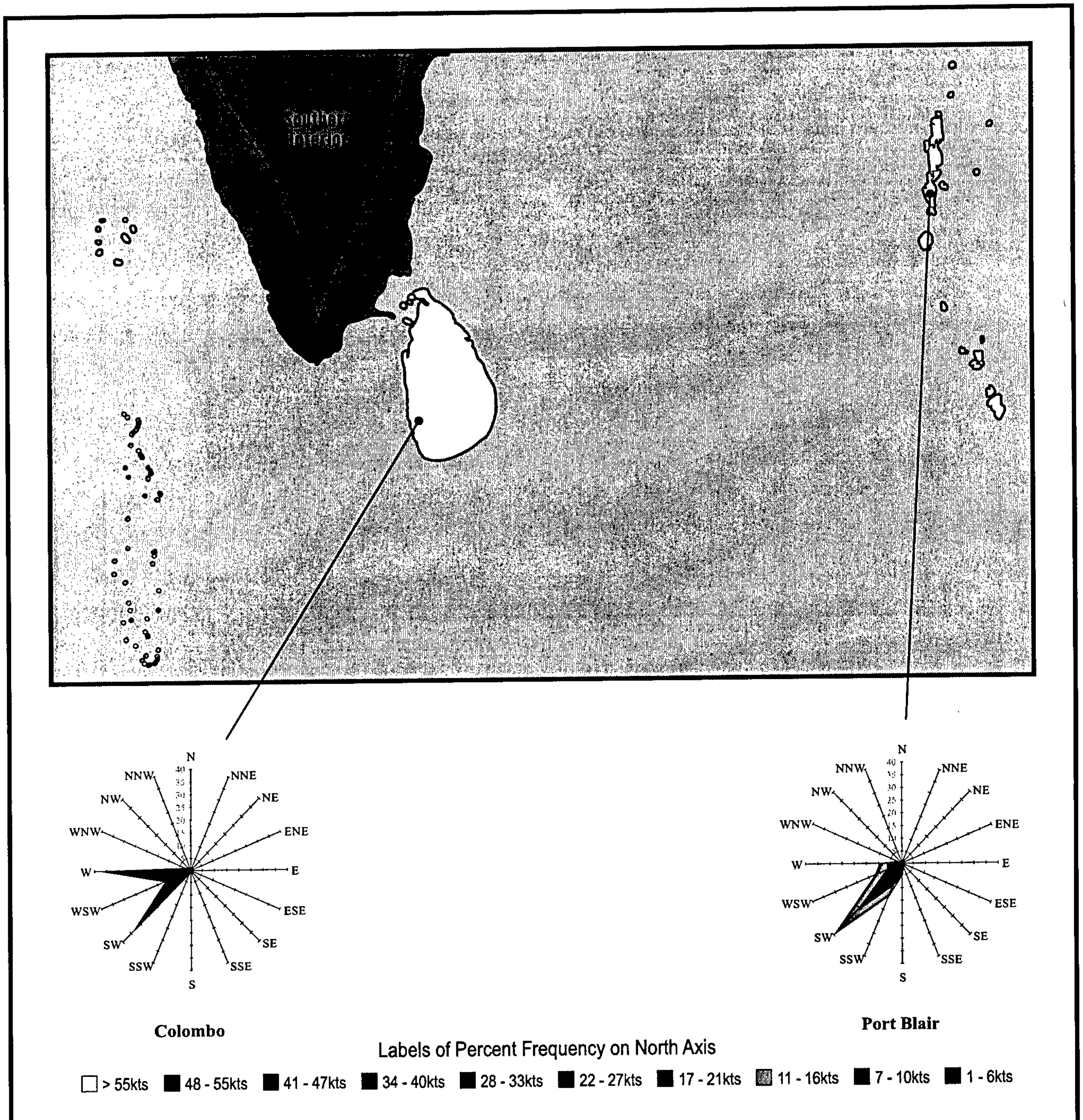


Figure 7-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Upper-air winds are from the west over Sri Lanka, except at the highest levels. Winds at 5,000 feet average 31-45 knots. Speeds increase to 41-60 knots at 10,000 feet. At 18,000, feet speeds decrease slightly, to 26-50 knots. At 30,000, feet winds are from the east at 61-90 knots. This easterly flow is the tropical easterly jet that exists over the area during the southwest monsoon. Figure 7-22 is a composite using Colombo, Port Blair and Gan and shows the typical upper-air winds in July across the South Asian Islands.

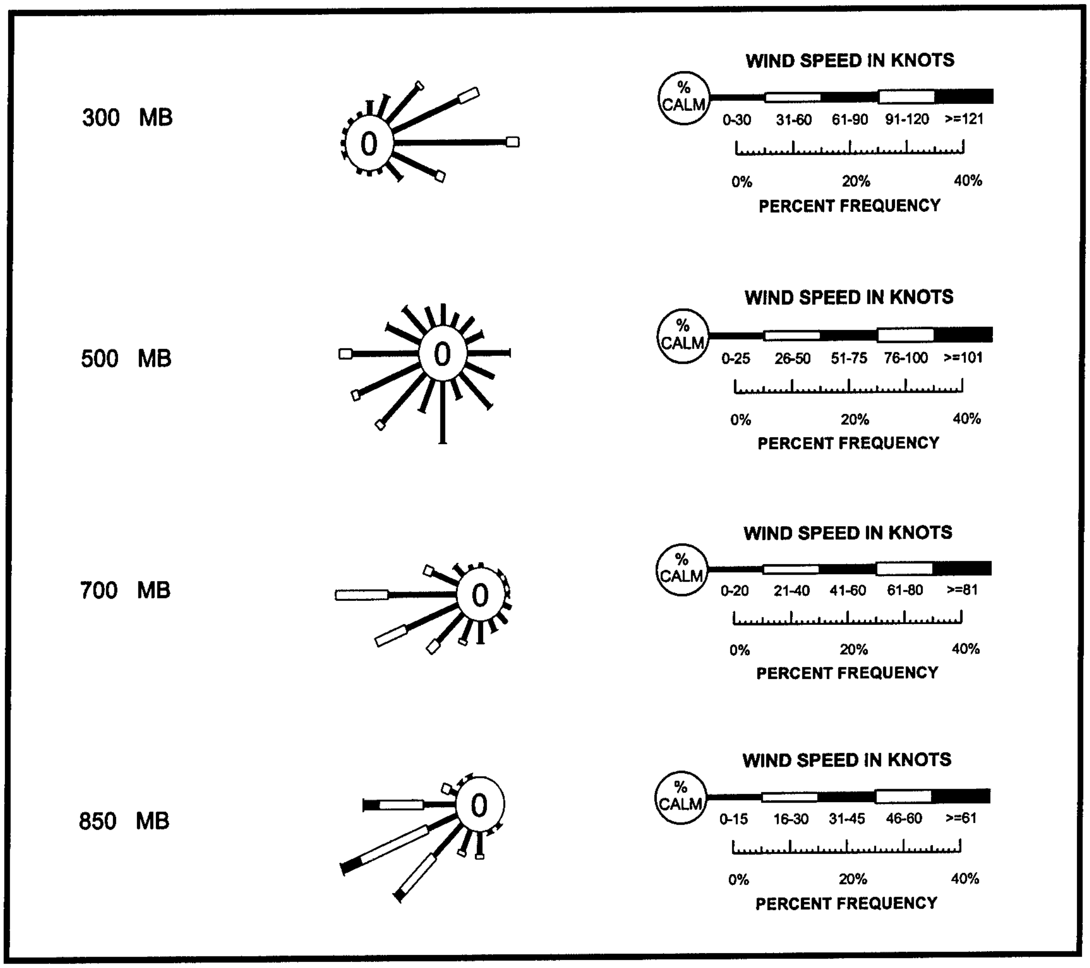


Figure 7-22. July Upper-Air Wind Roses. This wind roses composite using Colombo, Port Blair and Gan depicts wind speed and direction for standard pressure surfaces between 850 mb and 300 mb.

Precipitation. Figure 7-23 shows mean precipitation amounts for July in the South Asian Islands, and Figure 7-24 shows seasonal precipitation and thunderstorm days.

Sri Lanka. The southwest monsoon is in full swing. Rainfall is very different in the east and the west. In the east and in leeward highland sites, rain falls 3-9 days per month all season. The deeper in the rain shadow of the Central Highland, the fewer the rain days. June and July average 1-3 inches (25-76 mm) in these area. Most places have the same amounts in August, but the northeastern coast gets a bit more, 3.5-4.5 inches (89-114 mm). In September, amounts rise as the southwest monsoon winds weaken and the area averages 4-6 inches (102-152 mm). In the northwestern lowlands, convection tends to slide right past with no rain until the monsoon winds weaken. There it rains just 1-2 days in June through August and 4-6 days in September. It averages 0.5-1 inch (13-25 mm) in June through August and 2.5-3.5 inches (64-89 mm) in September. In the west and the windward highlands, rain falls 18-26 days per month all season, with the most days at the highest elevations. In June, these areas average 7-10 inches (175-254 mm) of rain in the lowlands and 12-20 inches (307-508 mm) at higher elevations. The higher the site, the more rain it gets. After the first heavy rains, amounts taper to 6-12 inches (152-307 mm) in July and August, then rise again in September to 10-18 inches (254-457 mm). Lightning is often observed in the distance, which means thunderstorm activity is greater than that shown in station reports. Soft hail is occasionally associated with the most violent storms. In the Central Highland, there are almost always thunderstorms in progress somewhere.

Nicobars and Andamans. The Andamans have more rain and rain days than the Nicobars. The Andamans average 11-14 inches (279-356 mm) of rain per month all season except at Port Blair and in the high elevations, where 18-22 inches (457-559 mm) fall each month. Port Blair gets so much because of terrain funneling. In the Nicobars, the average is 10-14 inches (254-356 mm) per month all season. In the Andamans, it rains 19-22 days per month all season. In the Nicobars it rains an average of 14-18 days per month. Thunderstorms occur most in June, 6-9 days throughout the area. In July through September, they occur 3-5 days per month.

Lakshadweeps and Maldives. In the Lakshadweeps, thunderstorms occur 2-4 days in June, 1-3 days in July and less than 1 day in August and September. Rain falls 22-26 days in June, 18-23 days in July, and 17-20 days in August and September, mostly as rainshowers. Most rain falls in convective showers in the Maldives as well; thunderstorms occur 6-9 days in June, 3-6 days in July, and 2-4 days per month in August and September. Rain falls 11-14 days in June, 8-10 days in July, and 8-10 days in August and September. The most rain falls in June in the Lakshadweeps, an average of 10-12 inches (254-307 mm). July and August see 8-10 inches (203-254 mm), and September averages 5-7 inches (127-178 mm). The Maldives average 6-8 inches (152-203 mm) in June and July and 4-6 inches (102-152 mm) in August and September.

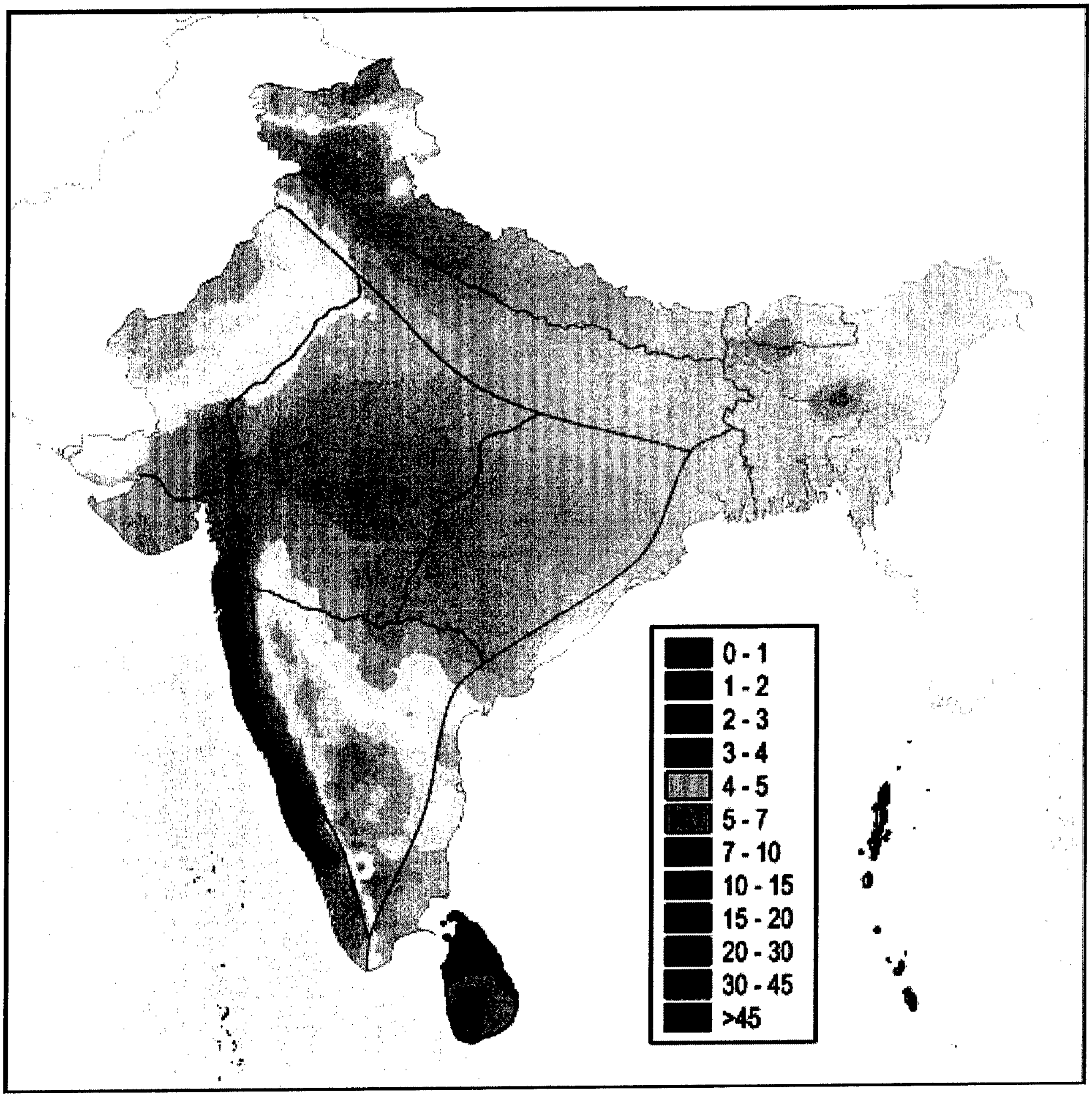


Figure 7-23. July Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

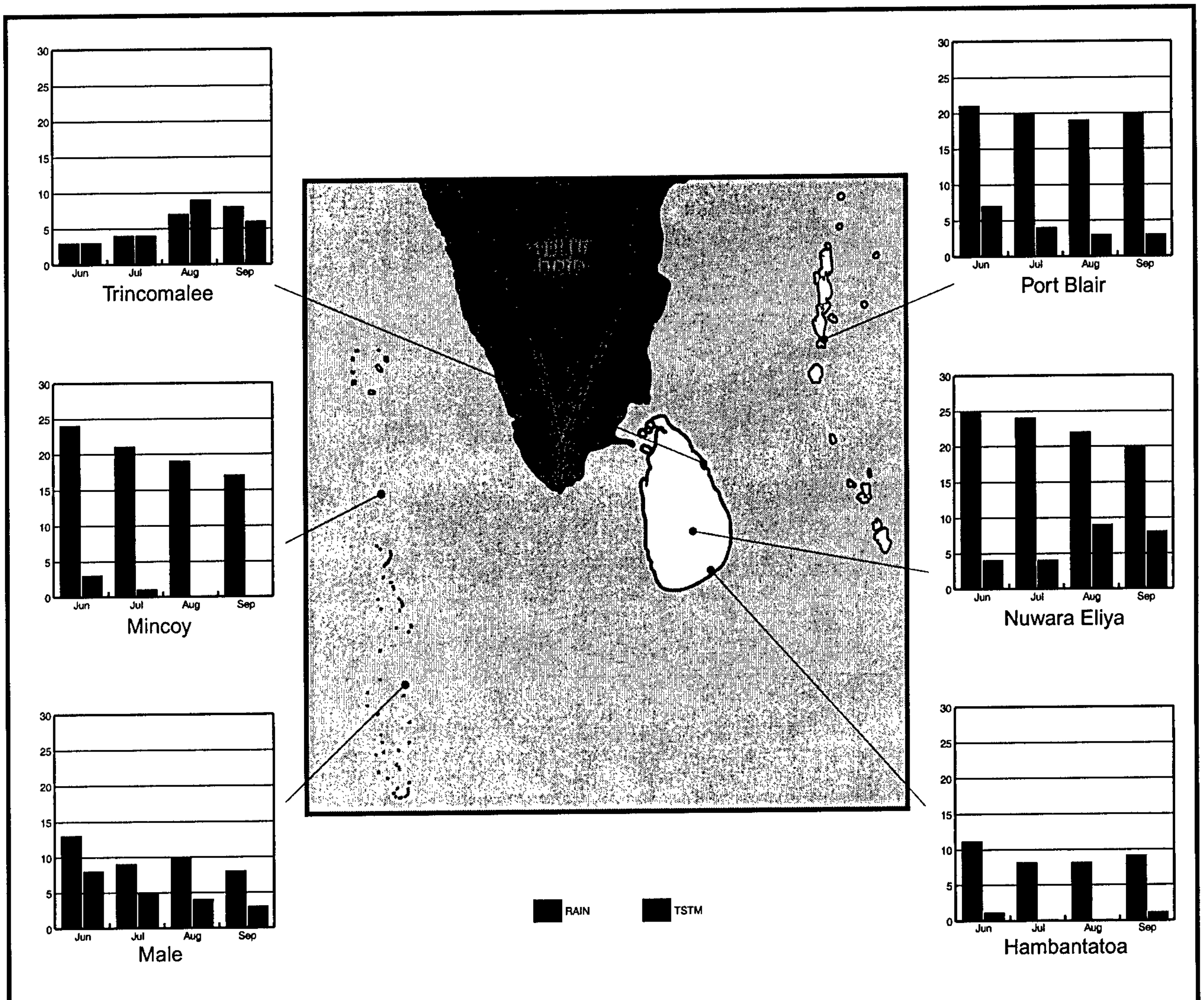


Figure 7-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm snow days for representative locations in the region.

Temperatures. Figure 7-25 shows the average July maximum temperatues for the South Asian Islands. Figure 7-26 shows the average minimum temperatures.

Sri Lanka. Mean highs are 86° to 92°F (30° to 33°C) in the eastern areas. Mean lows are 78° to 82°F (26° to 28°C). Extreme highs are 99° to 104°F (37° to 40°C). The highest temperatures occur in the southeastern part of the island. This area is subject to foehn winds during the southwest monsoon. These hot, dry winds bring some of the hottest temperatures to the island. In the west, temperatures are cooler. The mean highs are 85° to 89°F (29° to 32°C). Mean lows are 76° to 79°F (24° to 26°C). Extreme highs are 99° to 102° (37° to 39°C). Extreme lows are 66° to 70°F (19° to 21°C). As temperatures cool moist adiabatically with elevation, it is much cooler in the mountains. Temperatures at Nuwara Eliya range from 52° to 71°F (11° to 22°C).

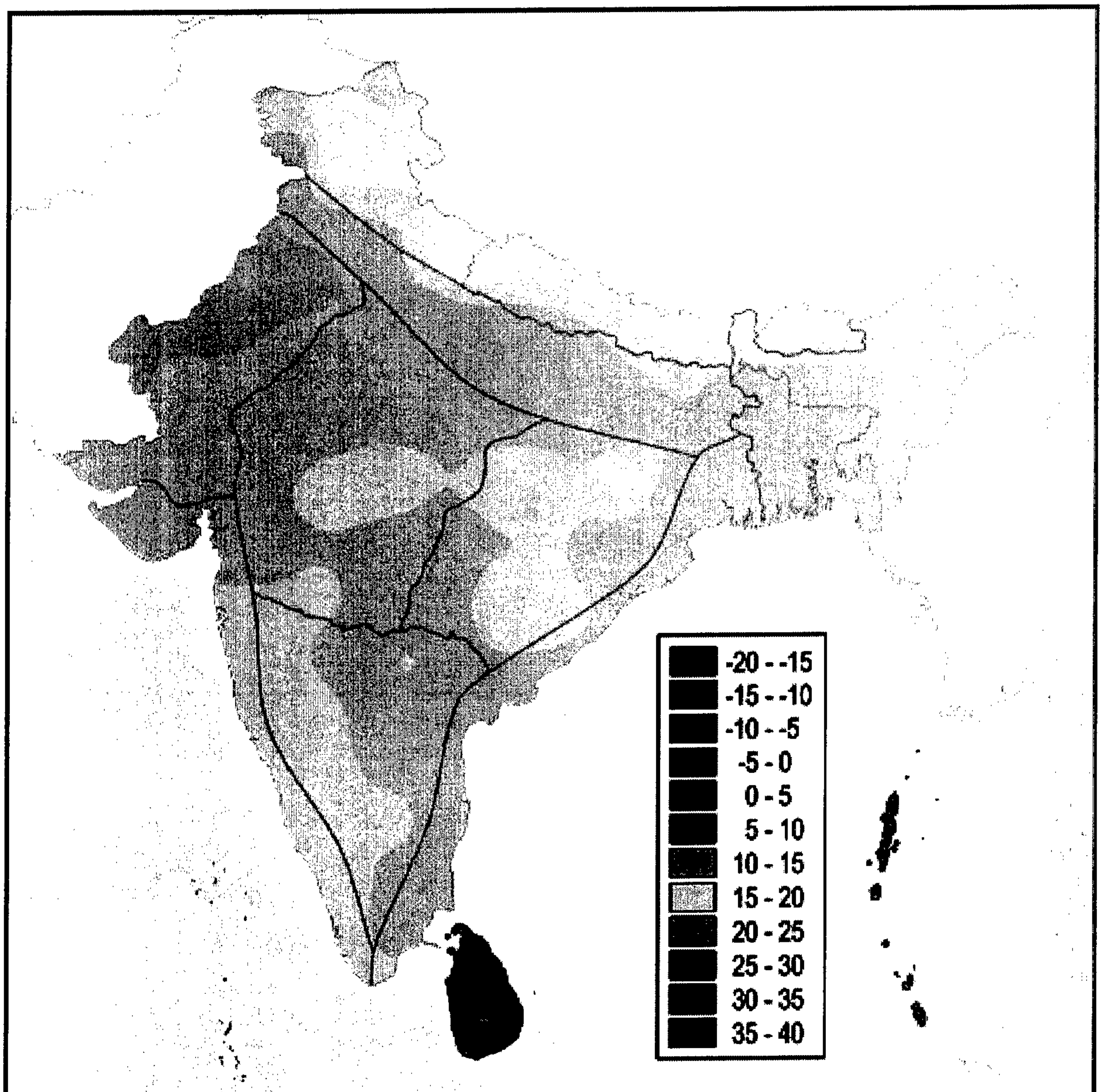


Figure 7-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher or low than the mean. Mean maximum temperatures during other months may be lower, especially at the beginning and ending of the season.

Extreme maximums are from 76° to 80°F (24° to 27°C) and extreme minimums are from 38° to 44°F (3° to 7°C).

Nicobars and Andamans. The mean highs are 84° to 86°F (29° to 30°C), and the mean lows are 75° to 77°F. The extreme highs are 90° to 96°F (32° to 36°C), hottest in the Andamans. The extreme lows are 61° to 67°F (16° to 19°C) in the Andamans and 71° to 73°F (22° to 23°C) in the Nicobars. Temperatures cool 3 Fahrenheit (1.5 Celsius) degrees per 1,000 feet (300 meters) elevation. This is significant in the Andamans.

Lakshadweeps and Maldives. Mean highs are 85° to 88°F (29° to 31°C), and mean lows are 75° to 77°F (25°C). Extreme highs are 90° to 93°F (32° to 34°C), and extreme lows are 69° to 72°F (21° to 22°C) in the Lakshadweeps only. The temperature does not fall below 75°F (24°C).

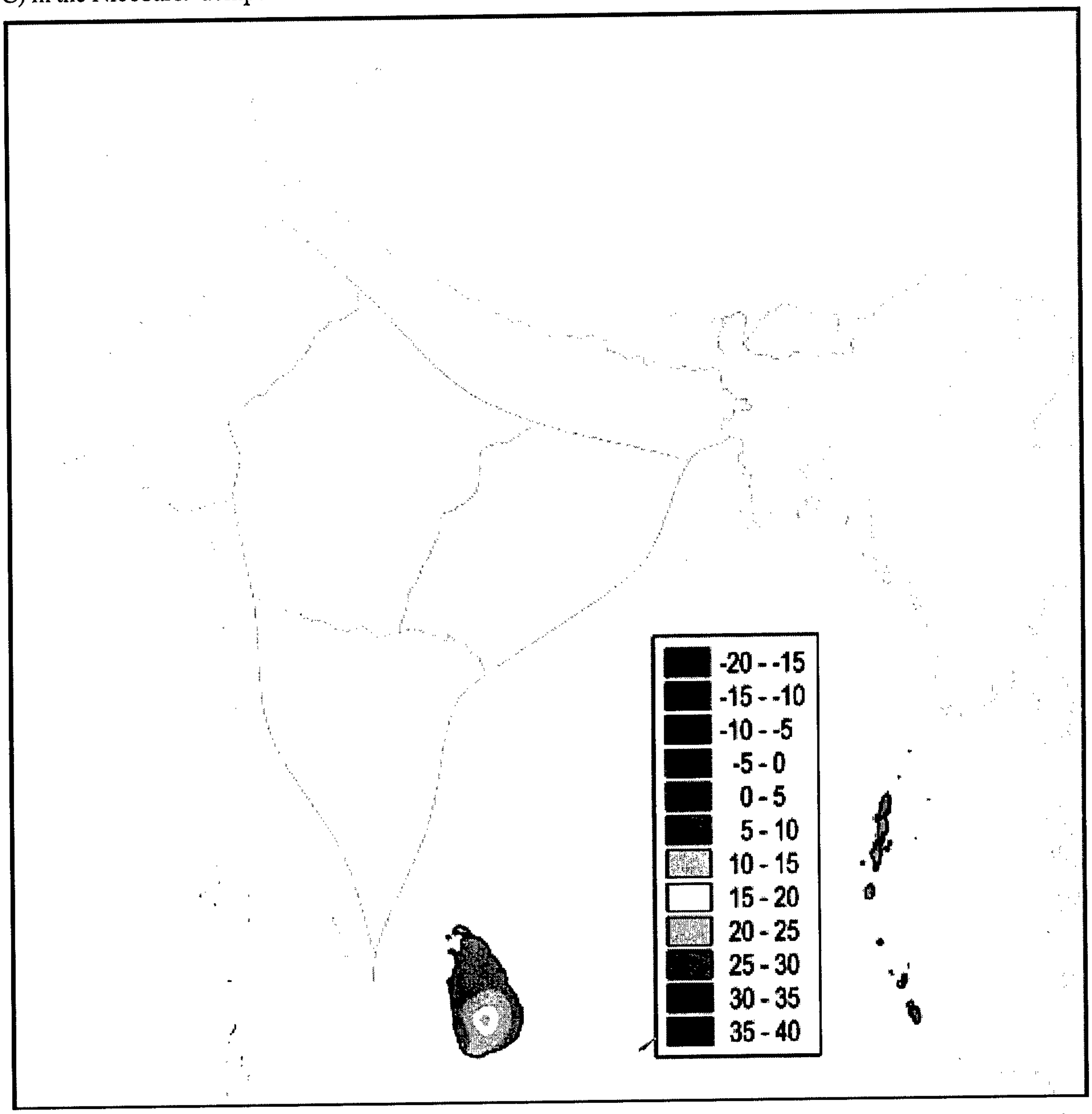


Figure 7-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often higher or lower than the mean. Mean minimum temperatures during other months may be lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. The rains of the southwest monsoon season end. The equatorial trough (ET) begins its retreat southward as the thermal low over Asia fades away. The withdrawal of the southwest monsoon occurs more slowly than the onset. The progression southward takes 2 months, begins quickly then moves more slowly, and is usually orderly. It occurs first in the northern-most part of the region. The ET is south of Sri Lanka by late November, but does not move south of the Addu Atoll (Maldives) until late in December. Heavy rains accompany the ET as it moves through an area.

The equatorial westerlies, the Somali jet, and the tropical easterly jet all disappear. The deep band of easterlies also retreats south in this phase. By the end of November, this band of easterlies will be largely south of the peninsula. The Asiatic high begins to form now, and wind flow at all levels is relatively ambiguous as a result. Because shear aloft is reduced in this transition season, this is when tropical cyclones have the best chance of developing and growing powerful. The Bay of Bengal is a favored breeding ground for tropical cyclones.

October and November are consistently more active tropical cyclone months than April and May. This is when Bay of Bengal water is warmest, and storms reach maximum occurrence rates. These storms are not as powerful as open ocean storms, but they still carry heavy rains and strong winds to the coasts. The mean storm track in this season is split. One branch directs storms to a landfall in the northeastern coastal area. The other directs them to the southern end of the peninsula to coastal areas just north of Sri Lanka. The southern track is the more active of the two. The Andaman and Nicobar Islands are unaffected by these storms, but easterly waves can still bring heavy weather to them until late November. The Lakshadweep Islands feel the remnants of these storms after they pass over the Indian peninsula, but the storms have no time to regenerate before moving west of the islands. The northern Maldives rarely experience anything but cloudy skies and some rain from the southern periphery of these storms.

Sky Cover. Figure 7-27 depicts seasonal percent frequency of ceilings less than 5,000 feet for selected South Asian Islands locations.

Sri Lanka. The Central Highland is the cloudiest area on the island, and cloud positions depend on the prevailing wind. At Nuwara Eliya, October ceilings below 5,000 feet occur 30-40 percent of the time overnight and into the morning hours, 65-70 percent of the time from late morning through the afternoon, and 50 percent of the time in the evening hours to midnight. The maximum rate is 80 percent of the time at mid-afternoon. In November, ceilings below 5,000 feet occur 40-50 percent of the time overnight through mid-morning, 60-70 percent of the time most of the day to early evening, and a maximum of 75 percent of the time at mid-afternoon. October and November ceilings below 1,000 feet occur 30-40 percent of the time most of the day and 50-60 percent of the time during the late morning to early evening hours. Ceilings below 500 feet occur 20-30 percent of the time at all hours with a maximum during the afternoon hours. Elsewhere on the island, the west side has ceilings below 5,000 feet an average of 30-40 percent of the time at all hours in October. In November, overnight ceilings at that level occur 15-25 percent of the time. During the day, especially in the afternoon hours, they continue to occur 30-40 percent of the time. Puttalam continues to have a higher rate of cloud cover, but the amounts are only 5-10 percent over the norm for the west side of the island. On the east side of the island, October ceilings below 5,000 feet occur 5-15 percent of the time in October and 10-20 percent of the time in November as the northeast monsoon flow begins to bring moisture ashore once again. The northern plains continue to have more cloud cover as they are essentially unsheltered from monsoonal flow from either direction and moisture is always available. There, ceilings below 5,000 feet occur 15-25 percent of the time overnight and into the morning hours and 45-55 percent of the time during the late morning to late afternoon. With the exception of the highlands (already covered), ceilings below 1,000 feet rarely occur.

Nicobars and Andamans. In October, ceilings below 5,000 feet occur 20-30 percent of the time most of the time and 55 percent of the time in the afternoons. By November, afternoon rates drop to 35 percent of the time while the rate remains the same for the rest of the day. Ceilings below 1,000 feet rarely occur in either month. In the Andamans, elevations above the LCL will still have cloud-cloaking but less in November than in October. Port Blair gets terrain-induced ceilings below 1,000 feet 5-9 percent of the time at all hours in both months. Other locations with the same configuration, on a lagoon and backed up against higher terrain, can expect the same rates. Elsewhere, ceilings below 1,000 feet are rare--; they almost never occur in the Nicobars.

Lakshadweeps and Maldives. Mean cloud cover is broken in October and scattered in November outside of the vicinity of the ET. In the ET area, broken sky cover can be expected, but mainly above 5,000 feet. Ceilings below 5,000 feet occur 5-10 percent of the time most of the day and 10-15 percent of the time in the afternoons. Ceilings below 1,000 feet do not occur outside of convective precipitation.

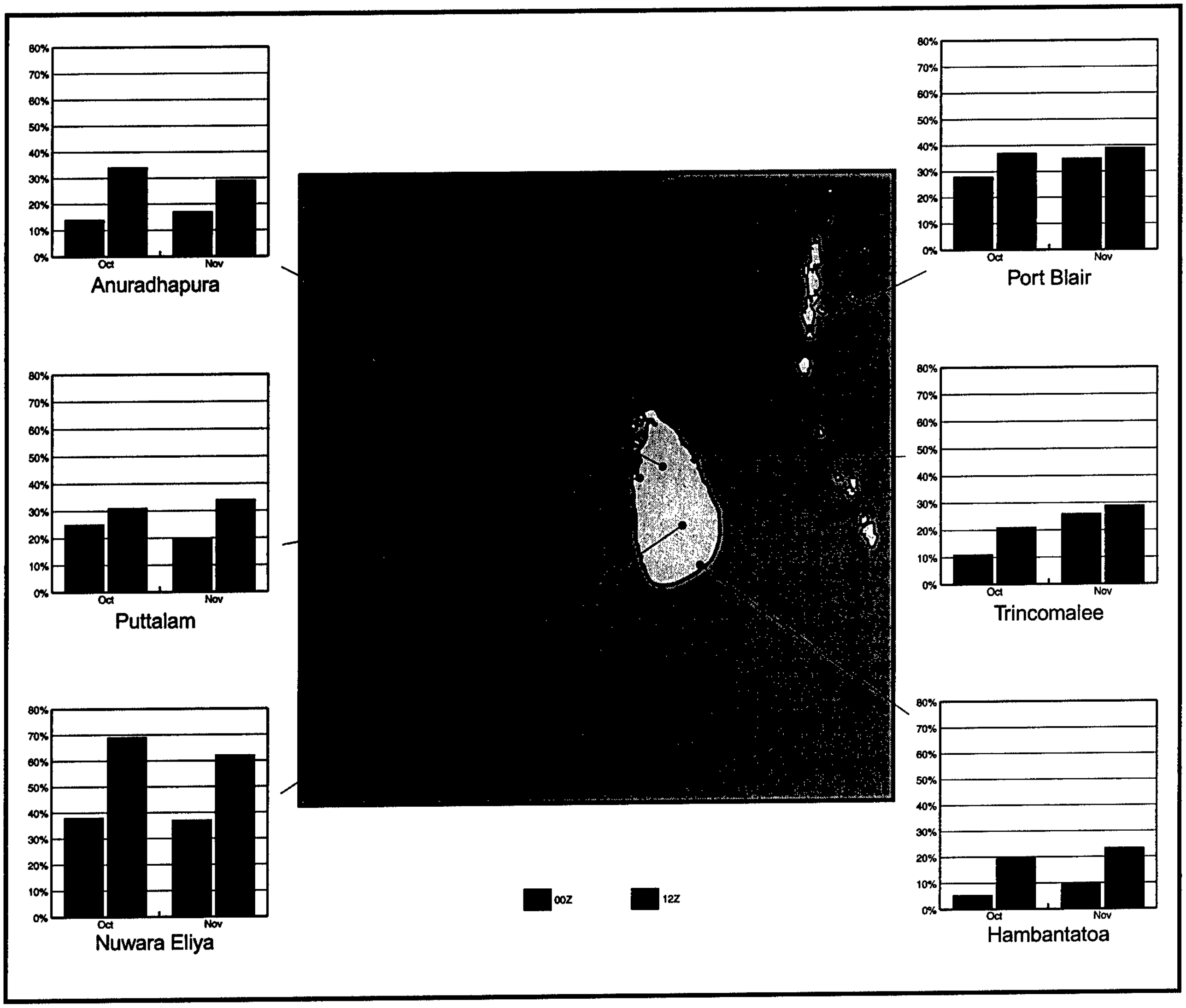


Figure 7-27. Post-Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Figure 7-28 depicts the post-monsoon seasonal percent frequency of visibility below 2 1/2 miles (4,000 meters) for selected South Asian Islands locations.

Sri Lanka. Visibility is good everywhere but in the elevations above the LCL. At Nuwara Eliya, visibility below 4,000 meters occurs 30-40 percent of the time from late afternoon to early morning and 5-10 percent of the time from mid-morning to late afternoon. Elsewhere on the island, visibility below 4,000 meters rarely occurs. Puttalam, on the inland coast of a west coast lagoon, gets it 10-15 percent of the time with afternoon rainshowers. Visibility below 1 1/4 (2,000 meters) rarely occurs anywhere outside of the highlands.

Nicobars and Andamans. Above the LCL, restricted visibility will occur in the highlands of the Andamans. Elsewhere, visibility below 4,000 meters rarely occurs.

Lakshadweeps and Maldives. Visibility below 4,000 meters occurs rarely, usually with convective precipitation for short periods.

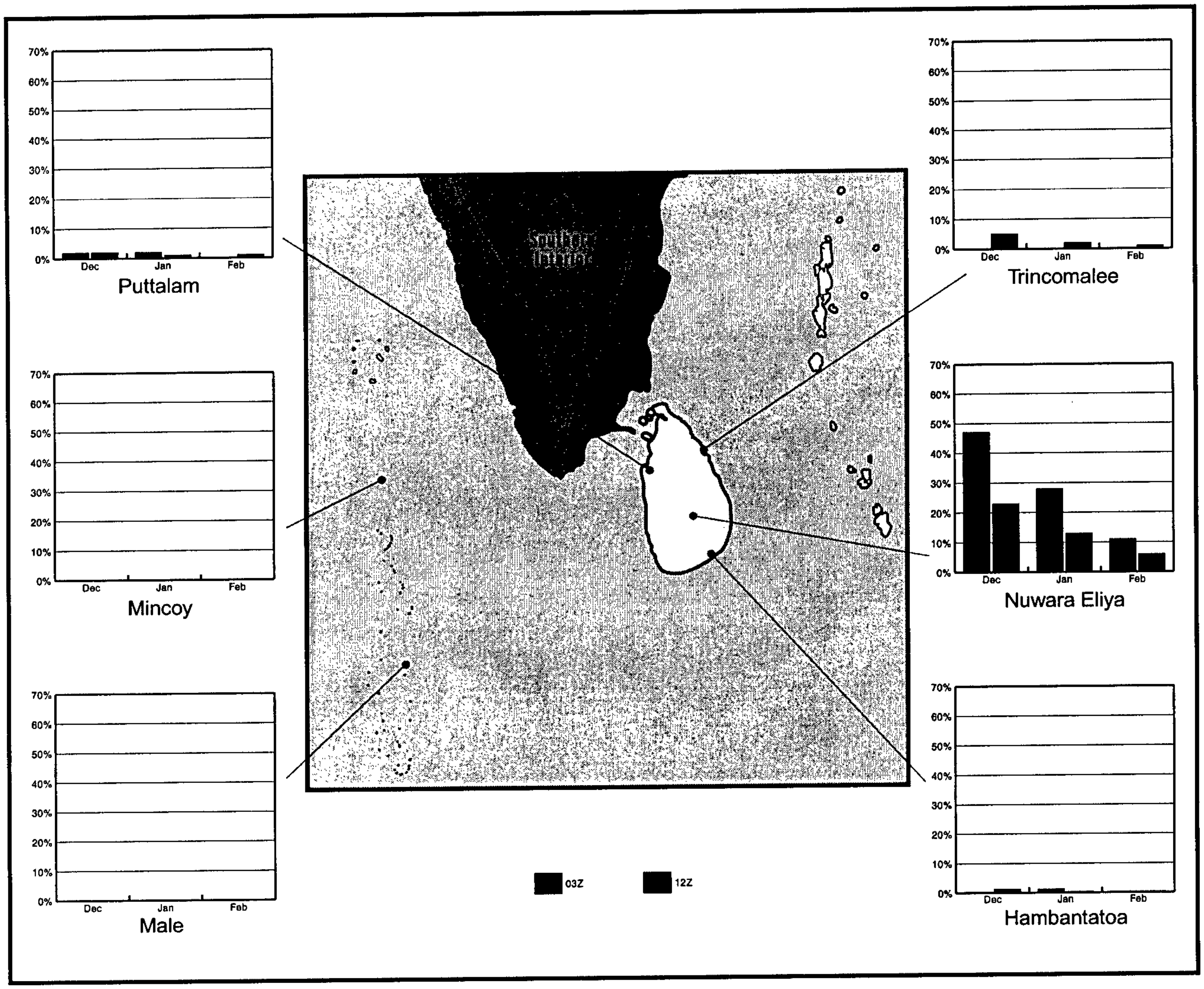


Figure 7-28. Post-Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Figure 7-29 shows surface wind roses in October for selected South Asian Islands locations.

Sri Lanka. In October, the northern half of the east coast is under weak northeast flow. On the west and south coasts, southwest flow still prevails but winds become more variable late in November, especially at night. Speeds are 6-10 knots, except at Hambantatoa on the south coast where winds are 8-15 knots. Interior winds are terrain-driven and vary with location relative to land features but speeds are generally light, under 5 knots. Calms occur roughly 50 percent of the time at night and 5 percent of the time during the day. On the northern east coast, calms occur 10-15 percent of the time at all hours. Farther south, they occur 30-40 percent of the time at night and 5-10 percent of the time during the day. On the northwest coast, calms occur 20-30 percent of the time at all hours. Farther south on the west coast and along most of the south coast, night calms occur 45-55 percent of the time and day calms occur 5-15 percent of the time.

Nicobars and Andamans. Winds in the Andamans are light and variable at all hours. North Andaman has calms 90-100 percent of the time at night and 70-80 percent of the time during the day. The rest of the Andamans have night calms 15-20 percent of the time, and day calms 40-50 percent of the time as local winds damp the weak northeasterly flow of the northeast monsoon. The Nicobars are under light southwesterly flow that goes light and variable by the end of November. Speeds average 5-10 knots. Calm occurrence rates vary widely between islands. The smallest islands tend to have some wind all the time. Larger islands have night calms 80-100 percent of the time and day calms 60-70 percent of the time.

Lakshadweeps and Maldives. Winds throughout this area vary from southwest to northwest. Speeds vary from 5-10 knots in the Lakshadweeps to 10-15 knots with gusts to 25 knots in the Maldives. Calms occur more in the Lakshadweeps than in the Maldives, 30-40 percent of the time at night and 5-15 percent of the time during the day. In the Maldives, calms occur only 5-10 percent of the time at all hours.

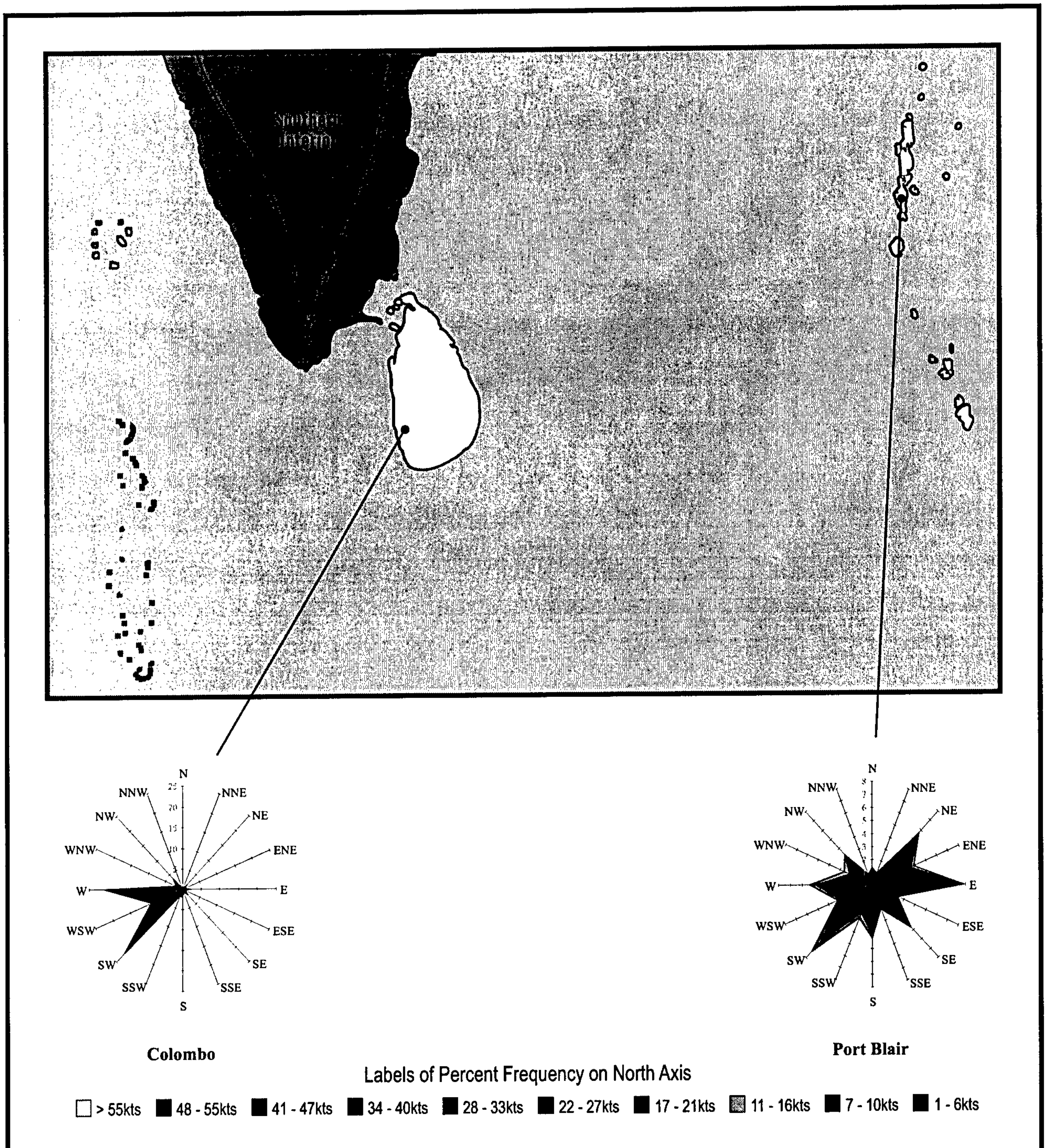


Figure 7-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The upper-air wind pattern is variable in November, but winds tend to flow from the northeast or east. At 5,000 feet the speed is 16-30 knots, 21-40 knots at 10,000 and 26-50 knots at 18,000 feet. At 30,000 feet, the winds are steady from the east at 31-60 knots. In December, winds are from the northeast at 5,000 feet at 16-30 knots. At 10,000 feet, the winds are from the east at 21-40 knots. East winds at 26-50 knots occur at 18,000 feet. At 30,000 feet, the winds are from the east at 31-60 knots. Figure 7-29 is a composite using Colombo, Port Blair and Gan and shows the typical Octoberl upper-air winds across the South Asian Islands.

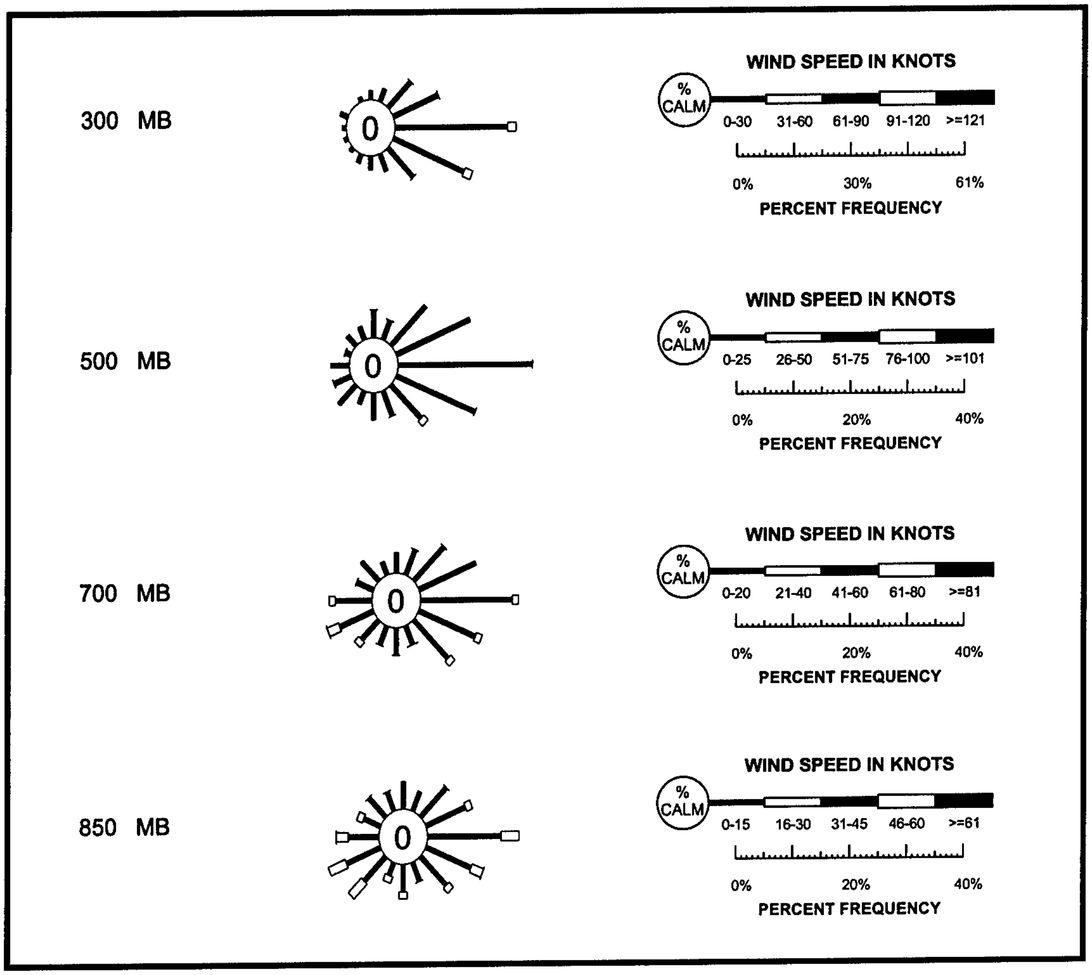


Figure 7-30. October Upper-Air Wind Roses. This wind roses composite using Colombo, Port Blair and Gan depicts wind speed and direction for standard pressure surfaces between 850 mb and 300 mb.

Precipitation. Figure 7-31 shows mean precipitation amounts in October for the South Asian Islands, and Figure 7-32 shows seasonal precipitation and thunderstorm days.

Sri Lanka. Under confused transition flow, local sea breeze showers occur often in places near the coast and daytime heating fires showers over the lowlands all over the island. Most lowland sites get 15-20 rain days in both months. As northeast winds begin to flow in November, the leeward sites on the west side of the island see a drop in rain, but it is minor, since strong flow does not set in until December, which allows local wind effects to override the large-scale flow. The average for all the lowland areas is 6-9 inches (152-229 mm) of rain in October. In November, the east side of the island gets more rain, an average of 10-14 inches (254-356 mm). The west side averages 6-9 inches (152-229 mm) at the same time. Sites at high elevations in the Central Highland get 15-19 inches (381-483 mm) of rain over 20-23 days in both months. Lightning is often observed in the distance, which means thunderstorm activity is greater than that shown in station reports. In the Central Highland, there are always thunderstorms in progress somewhere.

Nicobars and Andamans. Rain falls 14-18 days in October throughout the area and 10-15 days in November. The Nicobars have more thunderstorm days, 5-8 days in October and 4-6 days in November. The Andamans average 2-4 days in both months, although there are probably orographic thunderstorms over the mountains that go unreported. Rain amounts drop more sharply in the Andamans, from 12-15 inches (305-381 mm) to 8-10 inches (203-254 mm) in November. In the Nicobars, October sees 10-12 inches (254-305 mm) of rain and November averages 9-11 inches (229-279 mm).

Lakshadweeps and Maldives. The Lakshadweeps come under the northeast monsoon in this season. The northern islands average 7-9 days with rain and/or thunderstorms in October and only 4-6 in November. Southern islands average 12-16 days with rain and 1-2 thunderstorm days in both months. Heavy rains mark the position of the ET in the Maldives. Male gets heavy rain as the ET passes over in October on the way; more than 14 inches (356 mm) of rain fall over 17 days. In November, just over 5 inches (127 mm) of rain falls over 8 days. The southern Maldives are still under the southwest monsoon through November and average 4-6 inches (102-152 mm) of rain in both months over 8-10 days.

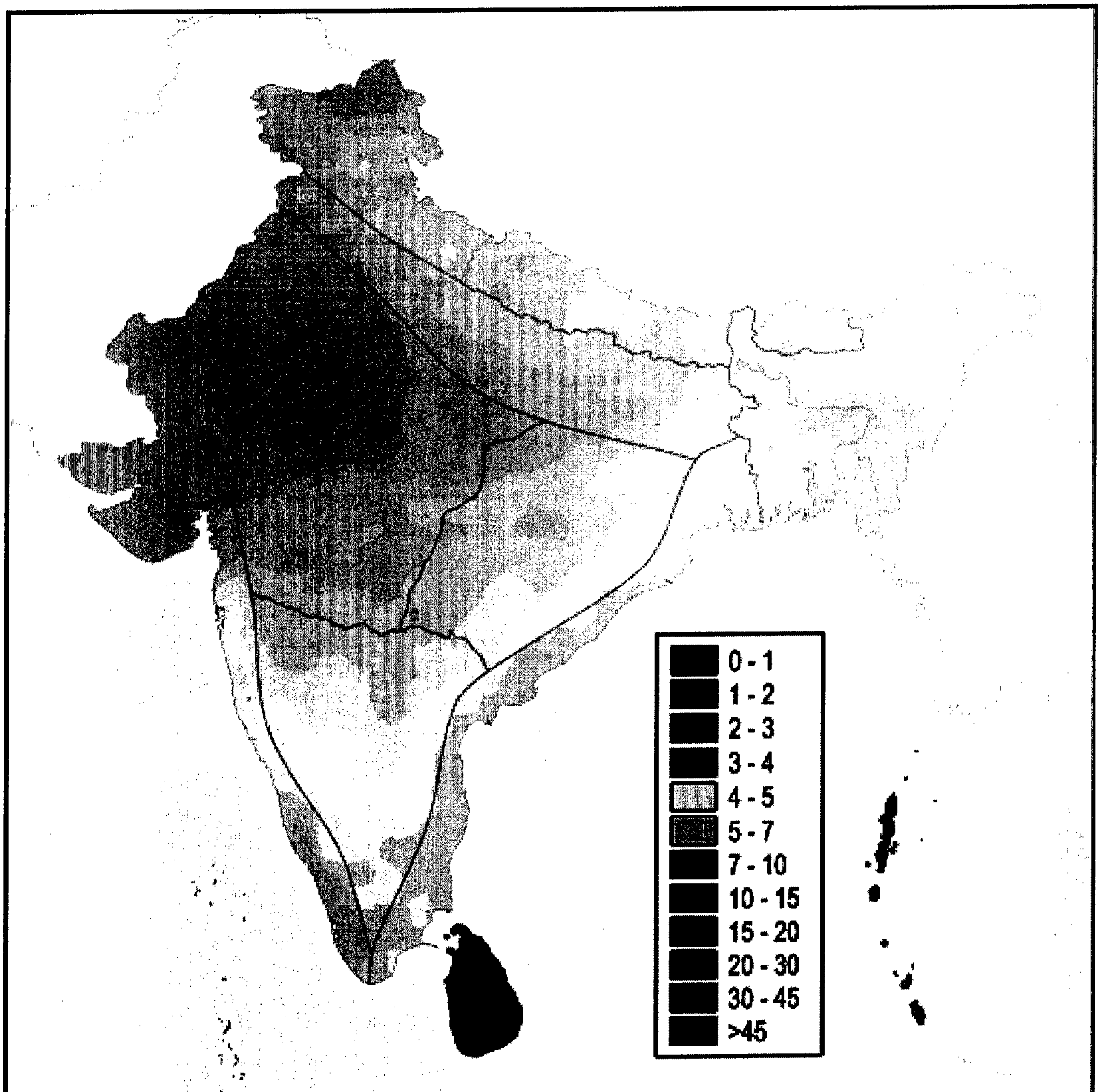


Figure 7-31. October Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

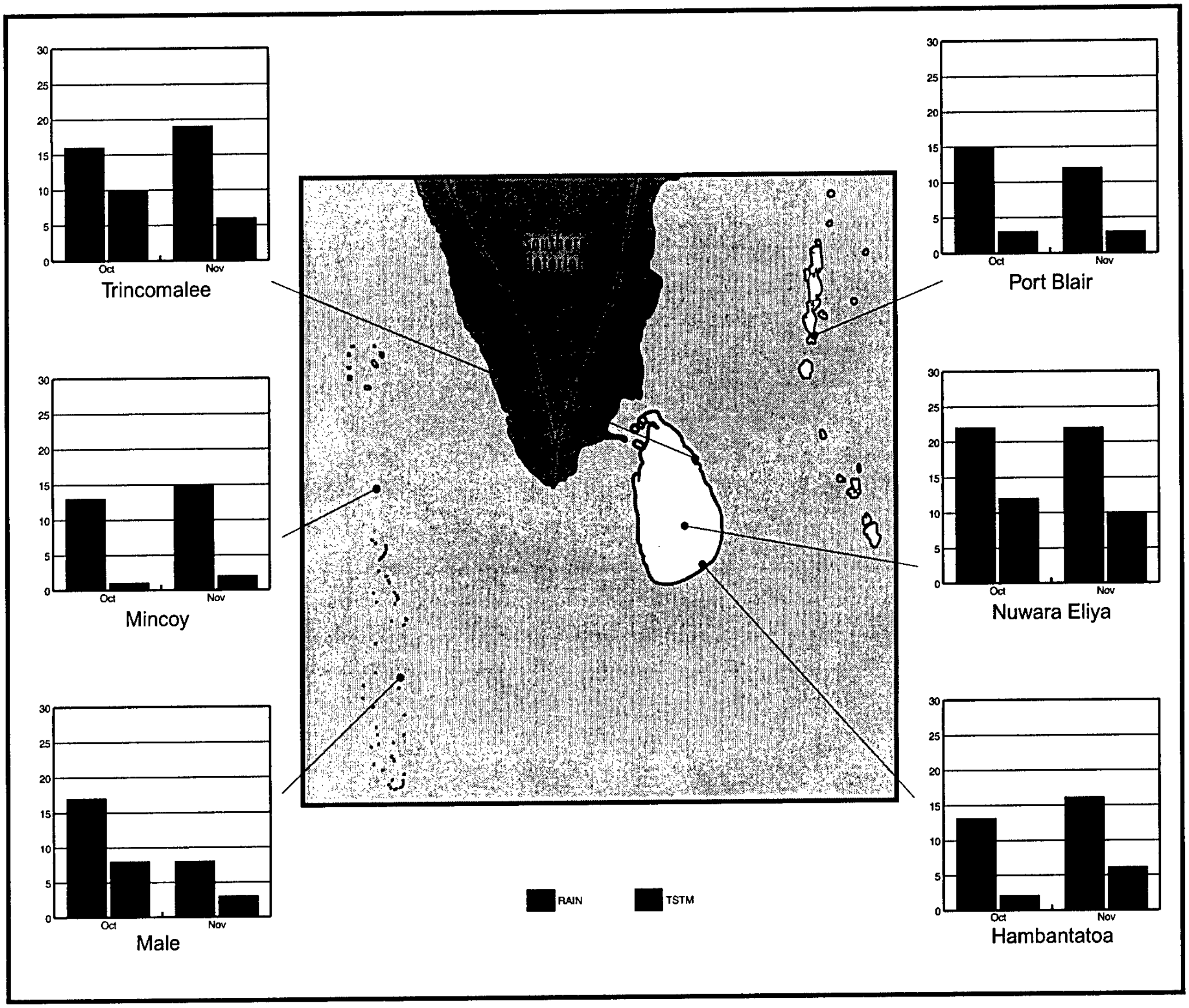


Figure 7-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Figure 7-33 shows mean maximum temperatures in October in the South Asian Islands, while Figure 7-34 shows mean minimum temperatures in October.

Sri Lanka. Mean highs are 81° to 83°F (27° to 28°C) in the east. Mean lows are 74° to 77°F (23° to 25°C). In the west, the mean highs are slightly warmer, 82° to 85°F (28° to 29°C), but the mean lows are the same as in the east. Extreme highs are 89° to 100°F (32° to 38°C). Extreme lows are 62° to 68°F (17° to 20°C). At high elevations in the mountain, the mean high is 68°F (20°C) and the mean low is 46° to 51°F (8° to 11°C). This occurs because temperatures cool moist-adiabatically, roughly 3 Fahrenheit (1.5 Celsius) degrees per 1,000 feet (300 meters) elevation. The extreme high

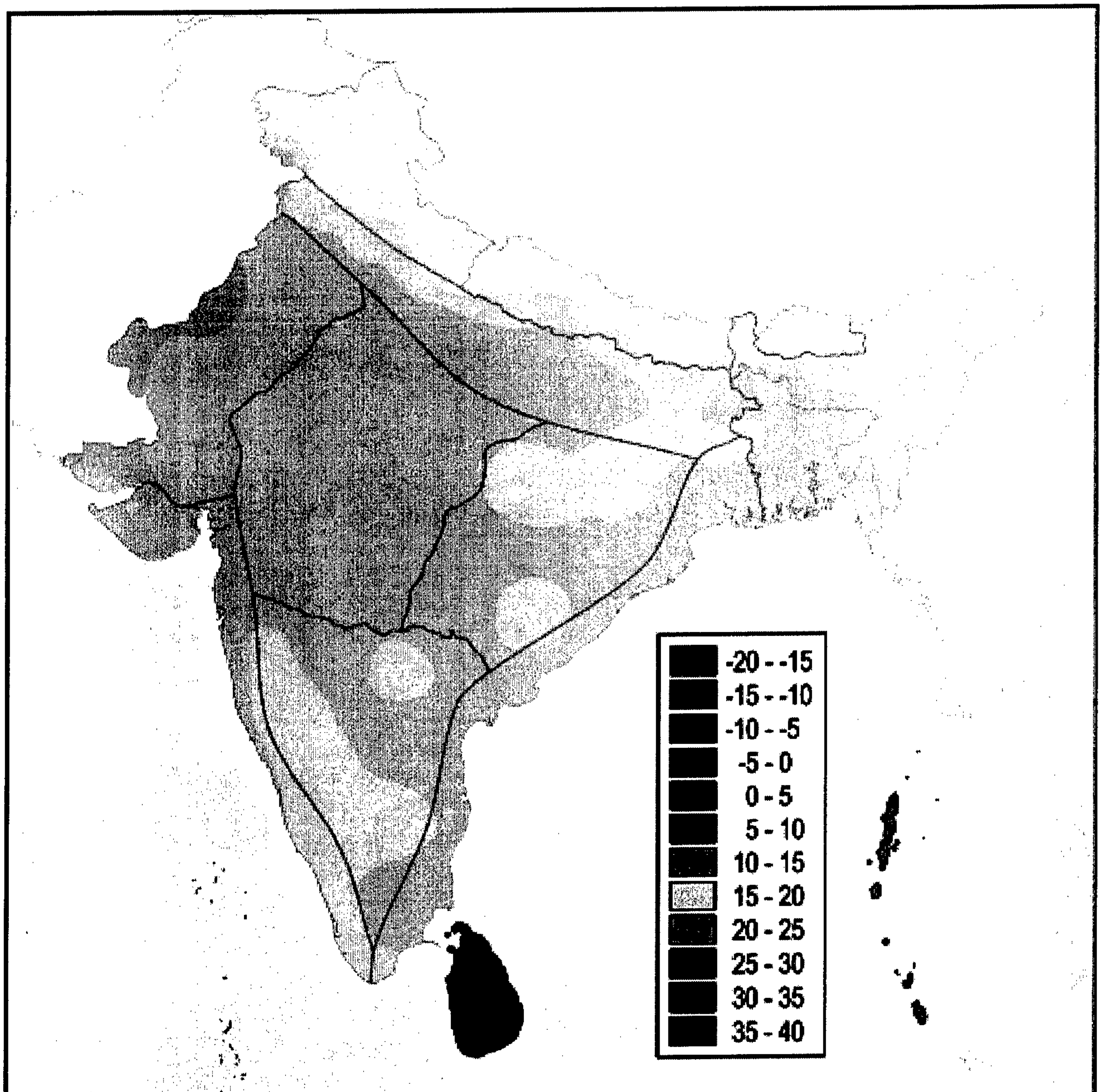


Figure 7-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for October. Daily high temperatures are often higher or lower than the mean. Mean maximum temperatures during November may be lower, especially at the end of the month.

is 75°F (24°C), and the extreme minimum lows are 30° to 34°F (-1° to 1°C).

Nicobars and Andamans. The mean highs are 84° to 87°F (29° to 31°C) and the mean lows are 74° to 76°F (23° to 24°C). The extreme highs are 89° to 98°F (32° to 37°C) and the extreme lows are 63° to 73°F (17° to 23°C). The warmest highs and coolest lows occur in the Andamans. The temperature never drops below 70°F (21°C) in the Nicobars. Temperatures cool moist-adiabatically, roughly 3 Fahrenheit (1.5 Celsius) degrees per 1,000 feet (300 meters) elevation. This is significant in the Andamans.

Lakshadweeps and Maldives. Mean highs are 85° to 87°F (29° to 31°C) and mean lows are 74° to 76°F (23° to 24°C). Extreme highs are 87° to 91°F (31° to 33°C), and extreme lows are 68° to 70°F (20° to 21°C) only in the Lakshadweeps. The temperatures do not fall below 72°F (22°C) in the Maldives.

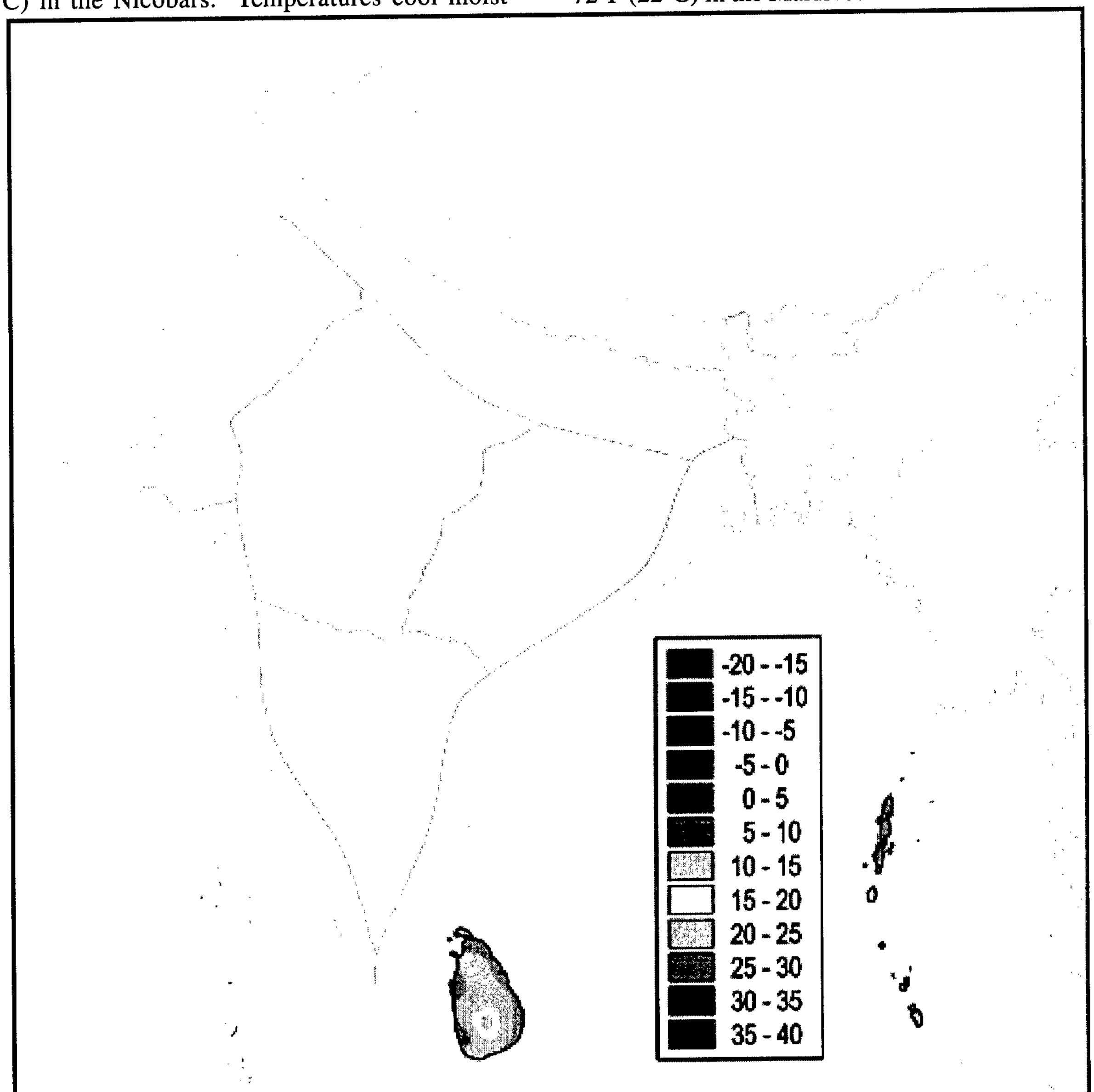


Figure 7-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for October. Daily low temperatures are often higher or lower than the mean. Mean minimum temperatures during November may be lower, especially at the end of the month.

BIBLIOGRAPHY

Alford, D., *Notes on High Elevation Research with Selected Bibliography*, Defense Technical Information Center, Fort Belvoir, VA, August 1965

Ananthakrishan, R., "Some Aspects of the Monsoon Circulation and Monsoon Rainfall," *Pure and Applied Geophysics*, Vol. 115, No. 5-6, pp 1209-1249, 1977

——— et al, "Some Features of the Southwest Monsoon Rainfall Along the West Coast of India," *Proceedings of the Indian Academy of Science,* Part A, Vol. 88A, No. 3, pp 177-199, 1979

Ananthasayanam, M. and Narashima, R., "Standards for the Tropical Indian Atmosphere," *Space Research, Vol. 20 - Proceedings of the Open Meetings of the Working Groups on Physical Sciences*, pp 25-58, 29 May -9 Jun 1979

Arkin, P., et al, "Indian Monsoon Rainfall, 1986-1987," National Weather Service, *Proceedings of the Twelfth Annual Climate Diagnostics Workshop*, pp 14-23, Mar 1988

Asnani, G. C., *Tropical Meteorology, Volume 1*, Noble Printers, Pune, India, 1993

Atkinson, G., and Sadler, J., *Mean-Cloudiness And Gradient-Level Wind Charts over The Tropics*, AWS TR 215 Vols. I and II, Air Weather Service, Scott AFB, IL, 1970

Awasthi, A., *Indian Climatology*, APH Publishing Corporation, New Delhi, 1995

Baker, B., *Glossary of Oceanographic Terms*, U.S. Naval Oceanographic Office, Washington DC, 1966

Bialek, E., *Handbook of Oceanographic Tables*, U.S. Naval Oceanographic Office, Washington DC, 1966

Cadet, D., "Meteorology of the Indian Summer Monsoon," *Nature*, Vol. 279, No. 5716, pp 761-767, 1979

Central Intelligence Agency, *Burma, Section 23: Weather And Climate*, Defense Technical Information Center, Fort Belvoir, VA, 1967

———, *Ceylon, Section 23: Weather And Climate*, Defense Technical Information Center, Fort Belvoir, VA, 1954

———, *India and Pakistan, Section 23: Weather And Climate*, Defense Technical Information Center, Fort Belvoir, VA, 1966

———, *Indian Ocean Islands, Section 23: Weather And Climate*, Defense Technical Information Center, Fort Belvoir, VA, 1959

Cheang, B., "Short-And Long-Range Monsoon Prediction In Southeast Asia," *Monsoons,* pp. 579-606, John Wiley & Sons, Inc., New York, 1987

——— and Tan, H., "Some Aspects Of The Summer Monsoon In South-East Asia May To September 1986," *Australian Meteorological Magazine*, Vol. 36, No. 4, pp. 227-233, 1988

Chen, R., "Characteristics of the Air Current and Sub-Synoptic Scale Events Within a Summer Monsoon Cyclone over the Arabian Sea," *Scientia Atmospherica Sinica*, Vol. 5, No. 3, pp 366-368, 1981

Chin, P. and Lai, M., "Monthly Mean Upper Winds And Temperatures over Southeast Asia And The Western North Pacific," *Royal Observatory Technical Memoir No. 12*, Hong Kong, 1974

Das, P., "Meteorology in India," *Current Science*, Vol. 50, No. 11, pp 473-479, 1981

Data, M. and Mukherjee, S., "Thunderstorm Activities in West Bengal 1968-1970," *Institution of Electronic and Radio Engineers Proceedings (India)*, Vol. 10, No. 4, pp 112-121, 1972

De, U., "Importance of Mountain Waves in Aviation and Weather Hazards Associated With It," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 60, No. 1, pp 217-226, 1994

Desai, B., "Conditions Associated with and Probable Causes of the Drought of 1899 and Other Droughts over the Indian Subcontinent During the Summer Monsoon," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 42, No. 2-3, pp 149-155, 1976

Dhar, O., et al, "Rainfall Distribution over Indian Subdivisions During the Wettest and the Driest Monsoons of the Period 1901-1960," *Hydrological Sciences Bulletin des Hydrologiques*, Vol. 23, No. 2, pp 213-221, 1978

——— et al, "Trends and Fluctuations of Seasonal and Annual Rainfall of Tamil Nadu," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 91, No. 2, pp 97-104, 1982

Ding, Y., "A Case Study of the Formation and Structure of a Monsoon Depression over the Arabian Sea," *Scientifica Atmospherica Sinica*, Vol. 5, No. 3, pp 267-280, 1981

Fein, J. and Stephens, P., *Monsoons*, John Wiley & Sons, New York, 1987

Gadgil, S., "Orographic Effects on the Southwest Monsoon: A Review," *Pure and Applied Geophysics*, Vol. 115, No. 5-6, pp 1413-1430, 1977

Glickman, T., *Glossary of Meteorology*, American Meteorological Society, Boston, 2000

Gopinathan, C., "Surface Temperature of the Equatorial Pacific Ocean and the Indian Rainfall," *Current Science*, Vol. 57, No. 21, pp 1163-1165, 1988

Goswani, B., "A Mechanism for the West-North-West Movement of Monsoon Depressions," *Nature*, Vol 326, No. 6111, pp 376-378, 1987

Hamilton, M., "Monsoons - An Introduction," *Weather*, Vol. 42, pp 186-193, 1987

Hastenrath, S., *Climate and Circulation of the Tropics*, D Reidel Publishing, Dordrecht, Netherlands, 1988

———, *Climate Dynamics of the Tropics*, Kluwer Academic Publishers, Dordrecht, Netherlands, 1991

———, *and Lamb, P., Climatic Atlas of the Indian Ocean, Part I: Surface Climate and Atmospheric Circulation*, The University of Wisconsin Press, Madison, WI, 1979

Higdon, M., et al, *East Asia: A Climatological Study, Vol. II, Maritime,* AFCCC/TN-97/003, Air Force Combat Climatology Center, Scott AFB, IL, 1997

Indian Journal of Meteorology, Hydrology, and Geophysics, Vol 28, No. 28, pp 251-252, 1977

Jayamaha, G., "An Analysis of Droughts in Sri Lanka," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 42, No. 2-3, pp 133-148, 1976

Joint Typhoon Warning Center (JTWC), *1995 Annual Tropical Cyclone Report* , U. S. Naval Pacific Meteorology and Oceanography Center West, Guam, 1995

Joint U.S. Navy/U.S. Air Force Climatic Study of the Upper Atmosphere, NAVAIR 50-1C-1/ AWSTR-89/001, Vol. 1, January, Naval Oceanography Command Detachment, Asheville, NC, 1989

———, NAVAIR 50-1C-4/ AWS/TR-89/004, Vol. 4, April, Naval Oceanography Command Detachment, Asheville, NC, 1989

———, NAVAIR 50-1C-7/ AWS/TR-89/007, Vol. 7, July, Naval Oceanography Command Detachment, Asheville, NC, 1989

———, NAVAIR 50-1C-10/ AWS/TR-89/010, Vol. 10, October, Naval Oceanography Command Detachment, Asheville, NC, 1989

Kane, R., "Relationship Between the Southern Oscillation/El Niño and Rainfall in Some Tropical and Midlatitude Regions," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 98, No. 3, pp 223-235, 1989

Kar, S. and Ramanathan, N., "Characteristics of Air Flow over Andaman Islands Including Precipitation," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 96, No. 2, pp 169-188, 1987

Khandeker, M. and Neralla, V., "On the Relationship Between the Sea Surface Temperatures in the Equatorial Pacific and the Indian Monsoon Rainfall," *Geophysical Research Letters*, Vol. 11, No. 11, pp 1137-1140, 1984

Koteswaram, P., "Climatological Studies of Droughts in the Asiatic Monsoon Area, Particularly India," *Proceedings of the Indian Natural Science,* Part A, Vol. 42, No. 1, pp 1-14, 1976

Krishnamurti, T.N., et al, *Monthly Weather Review*, Vol. 109, pp 344-363, 1981

Laing, A. and Fritsch, J., "Mesoscale Convective Complexes over the Indian Monsoon Region," *Journal of Climate*, Vol 5, pp 911-919, May 1993

McGregor, G. and Nieuwolt, S., *Tropical Climatology - An Introduction to the Climates of the Low Latitudes*, 2nd Ed., John Wiley & Sons, Chichester, UK, 1998

Meehl, G., "Coupled Land-Ocean-Atmosphere Processes and South Asian Monsoon Variability," *Science*, Vol. 266, No. 51883, pp 263-267, 1994

Meteorological Research Committee Air Ministry, *The Upper Air Circulation in Low Latitudes and Its Relation to Certain Climatological Discontinuities*, Defense Technical Information Center, Fort Belvoir, VA, January 1952

Mishra, D. and Jain, R., "Characteristics of Cloud Features Associated with Monsoon Depressions Observed in Satellite Imagery," *Indian Journal of Radio and Space Physics*, Vol. 8, pp 201-206, 1979

Mohana Roa, N., "Rainfall Fluctuations - Break-Associated Synoptic Systems," *Pure and Applied Geophysics*, Vol. 109, No. 8, pp 1877-1891, 1973

Mohanty, U. and Das, S., "On the Structure of the Atmosphere During Suppressed and Active Periods of Convection over the Bay of Bengal," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 52, No. 3, pp 625-640, 1986

Mooley, D. et al, "Relationship Between the All-India Summer Monsoon Rainfall and Southern Oscillation/Eastern Equatorial Pacific Sea Surface Temperature," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 94, No. 2, pp 199-210, 1985

——— and Parthasaranthy, B., "Indian Summer Monsoon and El Niño," *Pure and Applied Geophysics*, Vol. 121, No. 2, pp 339-352, 1983

Mooley, D. and Munot, A., "Variations in the Relationship of the Indian Summer Monsoon with Global Factors," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 102, No. 1, pp 89-104, 1993

Moray, P., "Periodicity of Drought Occurrence in India," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 42, No. 5, pp 407-416, 1976

Muraleedharan, P. and Prasanna Kumar, D., "Equatorial Jet - A Case Study," *Indian Journal of Marine Sciences*, Vol. 21, No. 1, pp 35-45, 1992

Nieuwolt, S., *Tropical Meteorology - An Introduction to the Climates of the Low Latitudes*, John Wiley & Sons, Chichester, 1977

O'Brien, J. and Hurlburt, H., *Equatorial Jet in the Indian Ocean: Theory*, Defense Technical Information Center, Fort Belvoir, VA, March 1974

Pant, G. and Rupa Kumar, K., *Climates of South Asia*, John Wiley & Sons, Chichester, 1997

Rajeevan, M., "Upper Tropospheric Circulation and Thermal Anomalies over Central Asia Associated with Major Droughts and Floods in India," *Current Science*, Vol. 64, No. 4, pp 244-247, 1993

Rakhecha, P. and Dhar, O., "A Study of Aridity and Its Fluctuations over Andhra Pradesh," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 42, No. 2-3, pp 195-202, 1976

Ramachandran, V. and Patniak, J., "A Note on the Variation of the Freezing Level over India," *Current Science*, Vol. 43, No. 5, pp 143-144, 1974

Ramage, C., *Forecasting Guide to Tropical Meteorology, AWS TR 240 Updated*, AWS/TR-95/001, Air Weather Service, Scott AFB, IL, 1995

Raman, C. and Rao, Y., "Blocking High over Asia and Monsoon Droughts over India," *Nature*, Vol. 289, No. 5795, pp 271-273, 1981

Ramanadham, R., et al, "Characteristics of the Tropopause over India," *Pure and Applied Geophysics*, Vol. 101, No. 9, pp 261-275, 1972

Ramaswamy, C., "A Normal Period of Large-Scale Break in the Southwest Monsoon over India," *Proceedings of the Indian Natural Science Academy*, Part A, Vol. 42, No. 1, pp 51-67, 1976

———, "Synoptic Aspects of Droughts in the Asiatic Monsoon Area," *Proceedings of the Indian Natural Science Academy*, Part A, Vol. 42, No. 2-3, pp 109-132, 1976

Rangarajan, G. and Rao, K., "Periodicity in Rainfall at Madras," *Proceedings of the Indian Natural Science Academy*, Part A, Vol. 87A, No. 11, pp 193-200, 1978

Rao, K., et al, "The Climatic Water Balance of India," *Memoirs of the India Meteorological Department*, Vol. 32, Part 3, pp 1-36, 1976

Riehl, H., *Climate and Weather in the Tropics*, Academic Press, London, 1979

Sadhuram, Y., "Variability in the Surface Wind Direction at a Coastal Site of Complex Terrain," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 96, No. 1, pp 59-67, 1987

Sarkar, S., et al, "Rain and Extent of Rain Cells over the Indian Subcontinent," Sixth International Conference on Antennas and Propagation, Vol. 2, pp 318-321, 1989

Sastri, A., "Effect of ENSO on Regional Monsoonal Rains - A Case Study for Central India," 7th Global Warming International Conference (GW7), 1-3 Apr 1996, Vienna, Austria

Satyan, V., et al, "Monsoon Cyclogenesis and Large-Scale Flow Patterns over South Asia," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 89, No. 3, pp 277-292, 1980

Senapati, P., et al, "Distribution of Rainfall in Coastal Region of Orissa," *Indian Journal of Power and River Valley Development*, Vol. 38, No. 6, pp 193-198, 1988

Sikka, D., et al, "Sub-Seasonal Scale Fluctuations of the ITCZ over the Indo-Pacific Region During the Summer Monsoon Season. I. Features over the Indian Region," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 95, No. 1, pp 47-73, 1986

Sinha, D., et al, "The Nor'wester Scenario: The Role of Internal Gravity Wave," *Proceedings of the Indian Natural Science Academy*, Part A, Vol. 60, No. 1, pp 171-179, 1994

Sopher, D., *Geography of Indian Coasts*, Defense Technical Information Center, Fort Belvoir, VA, May 1960